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Jennifer Wang

Maia Werner-Avidon

Lisa Newton

Scott Randol

Brooke Smith

See next page for additional authors

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Authors

Jennifer Wang, Maia Werner-Avidon, Lisa Newton, Scott Randol, Brooke Smith, and Gretchen Walker

Ingenuity in Action: Connecting Tinkering to Engineering Design Processes

Jennifer Wang

University of California, Berkeley

Maia Werner-Avidon, Lisa Newton, Scott Randol, Brooke Smith and Gretchen Walker

Lawrence Hall of Science, University of California, Berkeley

Abstract

The Lawrence Hall of Science, a science center, seeks to replicate real-world engineering at the *Ingenuity in Action* exhibit, which consists of three open-ended challenges. These problems encourage children to engage in engineering design processes and problem-solving techniques through tinkering. We observed and interviewed 112 visitor groups at the exhibit to understand how children engage in engineering behaviors extracted from the steps of a design process and to what extent they are aware of these processes. We found that all but one group exhibited engineering behaviors, and facilitation and collaboration positively correlated with engineering behaviors. The *Ingenuity in Action* exhibit establishes a successful framework of designing for engineering learning.

Keywords: engineering, museum, informal learning, exhibit, design, open-ended problems

Introduction

Engineers handle complex, messy problems to design and create solutions for the needs of society (NAE, 2008). The Lawrence Hall of Science (the Hall), Berkeley, CA, seeks to replicate this real-world engineering experience through its *Ingenuity in Action* exhibit, which challenges visitors to create their own design solutions to engineering problems. This paper details a multiple comparative case study of visitor behavior with respect to engineering and collaboration at three activities at the *Ingenuity in Action* exhibit and characterizes what we believe to be a successful framework for implementing engineering learning activities at science centers.

The field of engineering has advanced rapidly in recent decades, and traditionally, schools do not teach many modern skills associated with engineering (Committee on K-12 Engineering Education, 2009). These engineering "habits of mind," or the "values, attitudes, and thinking skills associated with engineering," include systems or design thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations (Committee on K-12 Engineering Education, 2009), similar to what the Partnership for 21st Century Skills (2010) calls for: modern skills in critical thinking and problem solving, communication, collaboration, and creativity and innovation.

Design activities can serve as a pedagogical approach to teach these engineering skills (Committee on K-12 Engineering Education, 2009; National Research Council, 1998). A design process is iterative and may include and repeat any of the following steps: understand the problem, brainstorm multiple designs, explore the implications of the designs, choose a design and create it, test and evaluate the design, and iterate and refine the design (Committee on K-12 Engineering Education, 2009; Lehrer et al., 2000). This process varies given the situation, problem, and approach—often engaging engineers in constructing, debating, and evaluating alternative solutions and learning from failure (Lehrer et al., 2000).

For children, design processes can be seen in tinkering and play (Resnick, 2006). We define tinkering as a hands-on open-ended activity that involves playing with and exploring materials and making things. The Hall joins other museums (e.g., the Ontario Science Centre, the Science Museum of Minnesota, the Lemelson Center at the Smithsonian, The Works in Minnesota, the Museum of Science, Boston, and the Oregon Museum of Science and Industry) in providing tinkering engineering programs that engage visitors differently than typical interactive exhibits with specific learning goals. Previous research (Blud, 1990; Brooks & Vernon, 1956; Rosenfeld & Terkel, 1982) demonstrates that typical interactive exhibits increase engagement and lead to a greater time spent at the exhibit when compared to static exhibits. In contrast, little research has been conducted to examine how tinkering exhibits engage visitors (New York Hall of Science, 2010). Arguments about the lack of educational value in play and tinkering exist (Wellington, 1990). However, research has shown that engaging in steps of design through play, such as tinkering, may develop future interest in engineering for young children (Habashi, Graziano, Evangelou, & Ngambeki 2008). Furthermore, because of its exploratory and experimental nature, tinkering may encourage more "what if" discourse (e.g. "What if we tried to interact this way?" or "What if we changed this thing?") and lead to the discovery of novel phenomena (Callanan and Jipson 2001). Further, we hypothesize that through exploring "what if" possibilities, tinkering may potentially reinforce the brainstorm, test, and refine behaviors of a design process. Finally, tinkering provides opportunities for learners to create something of their own; consequently, they gain control, and thus ownership, of their learning (Collins, 1996; Engle, 2006; Schoenfeld, 1994). Zheng, Brombage, Adam and Scrivener (2007) claim that free-choice activities with user-created products have the potential to better engage visitors because, in contrast to more traditional interactive exhibits, they allow visitors the freedom to create and test their designs. This type of free-choice learning experience with hands-on constructivist activities is more attractive to visitors and fosters greater creativity (Zheng et al., 2007), which is key to developing engineering habits of mind.

Designers of tinkering exhibits need to consider collaboration because visiting children are nearly always in groups (with adults and/or other children) and facilitators are often present at the exhibit. Both collaboration with peers and collaboration with adults are found to improve learning (Cohen, 1994; Vygotsky, 1978). Interacting with others allows learners to construct knowledge that they may not have been able to construct on their own (Chi, 2009). Mercer (2008) found that "planning, negotiation, and the joint construction of knowledge by partners correlated significantly with successful problem solving." Thus, collaboration may be an important behavior in promoting and developing engineering habits of mind.

The *Ingenuity in Action* exhibit

Ingenuity in Action is openly accessible, located on the main floor of the museum. It comprises three engineering activities: creating designs for a wind tube (*Fly High*), modifying variables for LEGO cars (*Design and Drive*), and building bridges to span a gap and support a weight (*Build a Bridge*).

To depict the visitor experience, we first describe the layout of the exhibit. The three activities of *Ingenuity in Action* are located in the lobby and directly past the lobby of the museum (see Figure 1). *Fly High* and *Design and Drive* are in the lobby and next to each other. Through the main entrance to the rest of the museum is *Build a Bridge*, directly behind and also accessible through *Design and Drive*. Since this is an exhibit, all activities are drop-in and unregulated in terms of crowd flow. There are no directional signs at the exhibit, with the exception of the title "Ingenuity in Action" placed high above the exhibit and an inconspicuous sign at *Fly High*. Thus, with very little direction and guidance, visitors are free to explore and play with the provided manipulatives.

A typical visitor interaction at this exhibit varies in duration from a few seconds to an hour. Generally, visitors first approach the *Fly High* activity because it is most accessible upon entrance to the museum. Visitors may then progress to the *Design and Drive* activity. Otherwise, they enter the rest of the museum and may or may not stop at *Build a Bridge*, depending on how crowded the activity is.

At *Fly High*, visitors choose from a variety of materials to create a design to be flown inside the wind tubes (see Figure 3). The activity offers two wind tubes, and each has unique properties: one has a mechanical fan that circulates air and the other has a centrifugal fan that blows air straight up. The materials available include binder clips, washers, cups, plates, pipe cleaners, paper, and cut Styrofoam noodles, and all are placed in transparent bins near the wind tubes. Oftentimes, visitors leave their designs at the table and bins, and these become available to subsequent groups. Many approaching visitors do not actually create a design product, and instead they test the materials alone or test the
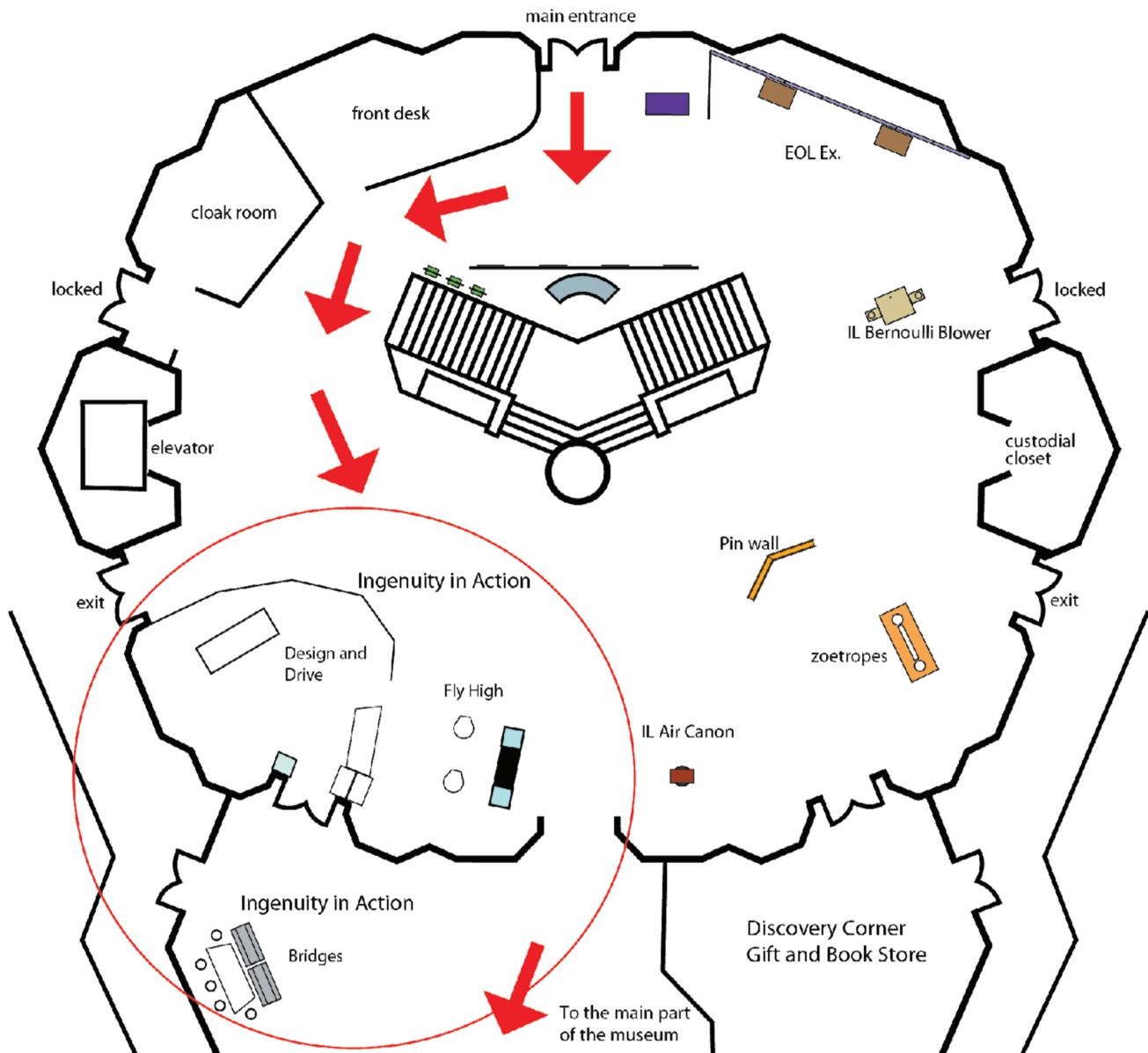
Figure 1. Layout of the museum lobby, including the *Ingenuity in Action* exhibit and its three activities. As can be seen from the layout, visitors can first access *Fly High*, then *Design and Drive*, and eventually progress to *Build a Bridge* beyond the lobby.

pre-made designs. There is an inconspicuous sign, as mentioned earlier, on a sheet of $8\frac{1}{2} \times 11$ inch paper and in a stand, which asks visitors to pick up after themselves on one side and has a basic design process ("design it, built it, test it") on the other side (see Figure 2).

At *Design and Drive* (see Figure 5), visitors choose from a set of pre-built LEGO cars on which they modify the wheel sizes and treads, and they build and change ramp structures. There are motorized and non-motorized cars. The two types of motorized cars are (a) geared for torque and (b) geared for speed. In addition to exploring gearing differences, visitors can explore three sizes of wheels, one of which is the standard rubber LEGO wheels while the other two are larger custom-made wheels lined with Velcro (see Figure 6). These two larger wheels can be further

customized by attaching various treads, including soft foam, rough non-skid tape, slippery wax, Astroturf, and bumpy plastic. The wheels and treads are located in accessible transparent bins. Visitors have the option of using existing ramps for the cars or designing their own by combining ramps of various inclines and lengths, as well as customizing the surfaces with soft foam, rough non-skid tape, Astroturf, or bumpy rubber treads.

At *Build a Bridge* (see Figure 7), visitors are provided with several rods, connectors, and cables to design and build a bridge that spans a specified gap or carries a specified weight, as chosen by the visitor or facilitator. The four basic pieces are made from metal and cable. Using these four kinds of pieces, visitors construct bridges across wooden blocks and can test their bridge by exerting forces at various points.

(re)design it.
Think of something that could float, twirl, or fly.

Wind Tubes

test it.
Test your design by putting it in the wind tube!

build it.
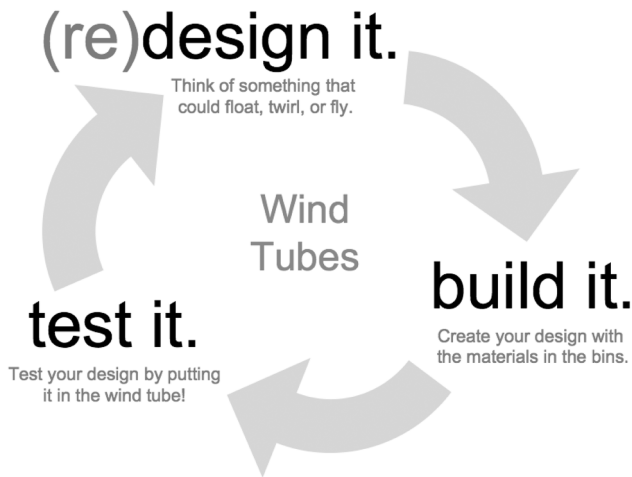Create your design with the materials in the bins.

Figure 2. Located at *Fly High*, this sign is printed on a piece of letter-sized paper and placed on top of the materials bin. The sign's size and location made it relatively inconspicuous, leaving it unnoticed by many visitors.

They can also construct a road across their bridge and test whether cars are able to cross the bridge successfully.

All of these components are facilitated by teenage and adult volunteers, staff members, and engineering students. The facilitator occasionally offers guidance in appropriate use of materials, possible design goals, and connections to engineering concepts. For instance, facilitators may ask guiding questions to help a visitor explicitly define a design goal at *Fly High* or provide verbal cues on the types of forces (tension vs. compression) to help the visitor refine the design at *Build a Bridge*. *Fly High* is the least facilitated activity and only occasionally has facilitators, who do not necessarily interact with the visitors. *Design and Drive* is always facilitated, but the facilitators usually only provide introductions to the exhibit, checking in and checking out the cars to visitors and describing how to use the cars. *Build a Bridge* is most heavily facilitated, typically with extended guidance from the facilitator.

Figure 4. An example of a design that visitors made at *Fly High*.

Research questions

In designing exhibits for engineering learning, engineers must consider what attracts visitors and what will prompt them to engage in engineering behaviors. Because nearly all visitor groups include children, this study will focus on children's behavior in engaging with the exhibit. The following research questions guided our study on the role of science centers in tinkering, specifically at the Hall's *Ingenuity in Action* exhibit:

Figure 3. The *Fly High* exhibit. Two bins are attached to a standing table on the left, and the two wind tubes are located nearby on the right.

Figure 5. The *Design and Drive* exhibit. Visitors enter at the left and can check out a car from the facilitator at that entrance. Bins with all the wheels and treads are located toward the back of the area, near the entrance. Ramps can be built and changed.
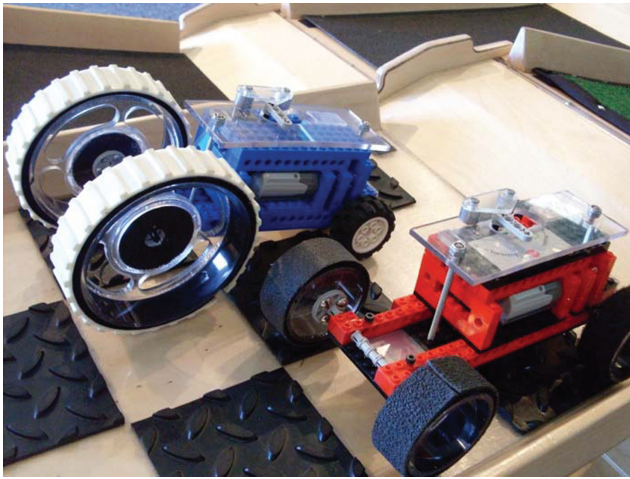
Figure 6. Two example designs of cars. The blue car is geared for torque, while the red car is geared for speed. There are three different wheel sizes: the small LEGO wheels (on the back of the blue car), medium custom wheels with optional treads (on the red car), and large custom wheels with optional treads (on the front of the blue car).

- How do properties of the different activities correlate with visitors' various engineering behaviors?
- To what extent are visitors aware of the activities' connection to engineering?
- How does collaboration correlate with engineering behaviors exhibited?

Figure 7. The Build a Bridge exhibit. Visitors sit at the table and build their bridges on wooden blocks using four types of pieces.

- What are the best kinds of facilitation for optimizing encounters with engineering thinking?

Because *Ingenuity in Action* consists of three separate design activities of varying levels of open-endedness and facilitation, we hoped to identify the common engineering behaviors across the activities and to understand what activity characteristics and features may be more successful at eliciting engineering behaviors. To do so, we used a multiple comparative case study of the three activities. By conducting a naturalistic case study, we were able to observe visitors engaging in truly free-choice and open-ended design.

Methods

In order to preserve real interactions at the museum, we conducted a naturalistic observation of how visitors interact with and understand the exhibit. We wanted to allow the natural flow of visitors through The Lawrence Hall of Science and to assess behaviors as they naturally happen, letting the complexities of the museum setting into our observations and interviews. Reasoning and learning behaviors are observable in the form of socially structured and embodied activity (Garfinkel, 1991). Thus, through observations, we examined visitor behavior through dialogue and actions, and through interviews, we probed deeper into visitor motivations and perceptions.

Participants

To determine the engineering behaviors of visitors and their awareness of the design process, we collected data from 112 visitor groups at the exhibit, totaling 286 individuals. Specifically, we conducted observations of 111 groups and interviews with 53 groups (one group was interviewed, but not observed). All participants were randomly chosen as they walked up and participated at the exhibit activities while the observer was on the museum floor. All but two visitor groups were family groups, consisting of children accompanied by adults. The other two groups were school groups, consisting of children accompanied by teachers and/or chaperones. The following graphs portray the demographics of the visitors; all groups included children as primary visitors with at least one child age 12 and under (see Figure 8) and the observed gender ratio of all individual visitors was fairly even (see Figure 8b).

Observations were conducted at all three activities: *Fly High*, *Design and Drive*, and *Build a Bridge*. We were able to obtain at least 29 observations at each activity (see Figure 9).

Procedure

In order to understand children's behavior in the context of the complex environment, we conducted observations of groups[1] and their interactions for the entire duration at a

Age of Observed Visitors (n=286)

Gender of Observed Visitors (n=286)

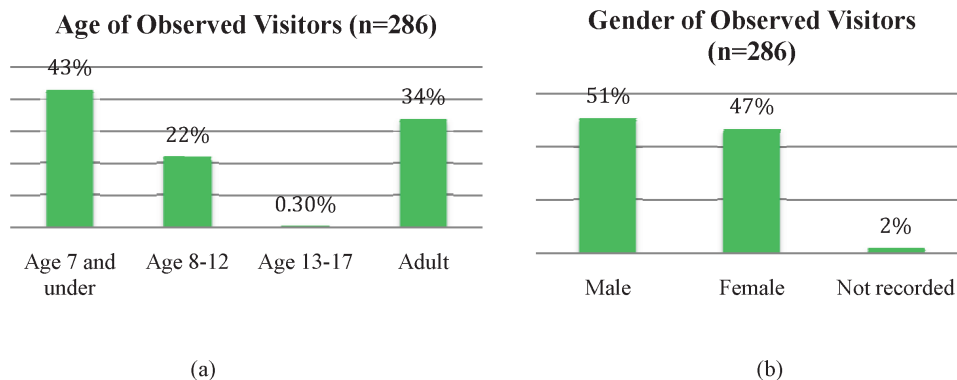(a)   (b)

Figure 8. (a) Age and (b) gender of observed visitors.

single activity and conducted interviews with available groups after the activity interaction. Five researchers, at separate times throughout the data collection, individually conducted observations of visitors' behaviors and interactions using a previously defined observation protocol. Each researcher then conducted follow-up interviews with the observed visitors who were not in a rush to leave and who were not too young (age 7 or older). These observations were recorded in the form of field notes in narrative form and coded (in real-time and immediately after the observation) in the protocol. The observation protocol was designed to document visitor demographics, time spent, activity completion levels, level of engagement, level of facilitation, affect displayed, and engineering behaviors exhibited (see Appendix A). The engineering behaviors explicitly outlined in the protocol, as shown below in Table 1, are based on the Museum of Science, Boston's Engineering is Elementary design process[2] (Museum of Science, Boston, n.d.). The depths of these behaviors were also noted by the observer on a scale of 1–3, with no mark if the behavior was not exhibited, 1 if the behavior was slightly exhibited, 2 if the behavior was moderately exhibited, and 3 if the behavior was strongly exhibited. The interview was designed to probe visitors' perception of the exhibit, what was learned, what was done, and whether they thought anyone did these activities in the real world (see Appendix B).

In considering interrater reliability, the protocol was discussed with all researchers to define the meanings of the marks and categories. Additionally, all but one of the researchers was part of the Hall's Research Group, which regularly conducts observations and interviews (the other researcher is a graduate student studying engineering education). As such, the protocol was developed as a

modification of other regularly used observation protocols, thus increasing the competence of the researchers.

Analysis

The researchers conducted real-time coding of the observation data. The interview data were coded by the Research Group. Variables from the observation protocol include date, activity, time, facilitator, group type, number in group, age, gender, activity completion level, engagement level, facilitation level, affect (presence of displeasure, frustration, confusion, neutral, surprise, intrigue/interest, excitement, pleasure), and engineering behaviors (both combined altogether and single specific behaviors). Variables from the interview include what the visitor did at the activity ("building," "testing/comparing," "making changes," "playing," "other"), who visitors thought did these activities in the real world ("scientists," "people who make things," "engineers, designers, or architects," "no one," "other"), what visitors felt they learned, whether there was anything frustrating about the activity, how fun the activity was, how interesting the activity was, and what could be improved at the activity.

To assess differences in continuous variables across groups, we performed analysis of variance (ANOVA) on the observation and interview data at a 5% and 10% significance level. To assess differences in categorical variables across groups, we performed Pearson's chi-square

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[1] When referring to visitor groups or visitors, we are focusing on the primary exhibit users of the group, who are generally the children age 12 and under.

[2] Other design processes are outlined by NASA (2008), Lehrer et al. (2000), Dym, Agogino, Eris, Frey and Leifer(2005), and the Committee on K-12 Engineering Education (2009). All reduce down, however, to the Museum of Science's most basic framework of a design process.

Number of observations (by activity)

Figure 9. Number of observations at each activity.

Table 1
The engineering design process and behaviors (extracted from Museum of Science, Boston's Engineering is Elementary curriculum) coded for during observations, as outlined in the observation protocol

Step 1: Identify	Step 2: Brainstorm	Step 3: Build	Step 4: Test, Refine Communicate
Expresses a design goal	Explores materials and variables	Manipulates variables to acheve goals	Tests design
Describes/identifies problem to be solved	Selects appropriate materials from availables options	Collaborates with others on design	Modifies designs to make improvements
	Describes one or more options for achieving goal	Create innovative disign	Tests revised designs
	Makes causal inference/prediction about how design will perform		Compares two (or more) designs
	Sketches designs		Discusses what works, what doesn't, or what could be improved
			Disscusses how activity relates to real world, engineers, etc.

test on the data at a 5% and 10% significance level. Finally, we used multiple linear regression to determine whether collaboration and facilitation significantly correlated with other variables while controlling for activity.

Findings

How do properties of the different activities correlate with visitors' various engineering behaviors?

To understand whether certain activities within the exhibit are better at engaging visitors in engineering behaviors than others, we conducted analyses to compare the behaviors exhibited at each of the three activities. We found significant differences between activities for certain types of engineering behaviors, the amount of time spent ($p = 0.003$), the facilitation level ($p < 0.001$), activity completion level ($p = 0.005$), and some affect. However, we found that there was no significant difference in the overall number of engineering behaviors exhibited. The interviews also revealed no significant difference on how fun or interesting the activity was.

Engineering behaviors
All groups but one exhibited engineering design behaviors, with an average of 5–6 behaviors out of the 15 listed in Table 1 (excluding the behavior discussing how the activity related to the real world, since this was added later). These findings indicate that the *Ingenuity in Action* exhibit engages visitors in engineering design behaviors.

In particular, we found that the exhibit was generally more successful in eliciting behaviors related to steps 3 and 4 (building, testing, and refining, with the exception of communicating) of our defined design process (see Table 1) and less successful in eliciting behaviors related to steps 1 and 2 (identifying and brainstorming), as well as communicating in step 4. Overall, the four most observed behaviors were "selects appropriate materials

from available options" in step 2 (70%), "tests design" in step 4 (63%), "manipulates variables to achieve goals" in step 3 (62%), and "tests revised designs" in step 4 (45%).

By activity, visitors at *Fly High* mostly engaged in the testing behaviors (see Figure 10): selecting appropriate materials (59%), exploring materials (59%), and testing designs (61%). Visitors at *Design and Drive* engaged in more test and refine: testing designs (79%), modifying (68%) and retesting designs (71%), and selecting appropriate materials (64%). *Build a Bridge* visitors most commonly engaged in planning and building behaviors: selecting appropriate materials (94%) and manipulating variables to achieve a goal (81%). They also much more frequently engaged in collaborating (52%) compared to other groups. This group was also the only one that discussed how the activity relates to the real world (36%).

For level of behaviors reached, there was typically no significant difference between activities. Overall, behaviors related to building, testing, and refining were observed at higher levels on a scale of 1–3 (1 if the behavior was slightly exhibited, 2 if the behavior was moderately exhibited, and 3 if the behavior was strongly exhibited; see Figure 11). The four behaviors exhibited at the highest levels were "modifies design to make improvements" in step 4 (2.05), "manipulates variables to achieve goals" in step 3 (2.00), "tests revised designs" in step 4 (1.96), and "compares two or more designs" in step 4 (1.91). Our interviews also confirm our observations; when asked what they did at the activities, visitors most frequently described building, testing or comparing, and making changes.

Time, facilitation, completion level, and affect
Figure 12 shows visitors spent an average of 12 minutes at *Fly High*, 13 minutes at *Design and Drive*, and 22 minutes at *Build a Bridge*. One group at *Build a Bridge* even spent 75 minutes at the exhibit. Fairly correspondingly, *Fly High* is frequently observed to be

Engineering Behaviors (by activity) (**p<0.05, *p<0.10)

- Fly High (n=51)
- Design and Drive (n=28)
- Build a Bridge (n=31)

Expresses a design goal — 27%, 21%, 32%

Describes/identifies problem to be solved — 35%, 29%, 42%

Explores materials and variables* — 59%, 46%, 32%

Selects appropriate materials from available options** — 59%, 64%, 94%

Describes one or more options for achieving goal — 18%, 21%, 16%

Makes causal inference/prediction about how design will perform — 12%, 7%, 6%

Sketches design — 0%, 0%, 0%

Manipulates variables to achieve goals** — 53%, 57%, 81%

Collaborates with others on design** — 27%, 18%, 52%

Creates innovative design — 20%, 11%, 19%

Tests design* — 61%, 79%, 52%

Modifies designs to make improvements** — 35%, 58%, 68%

Tests revised designs** — 37%, 71%, 32%

Compares two (or more) designs** — 14%, 50%, 6%

Discusses what works, what doesn't, or what could be improved — 18%, 32%, 35%

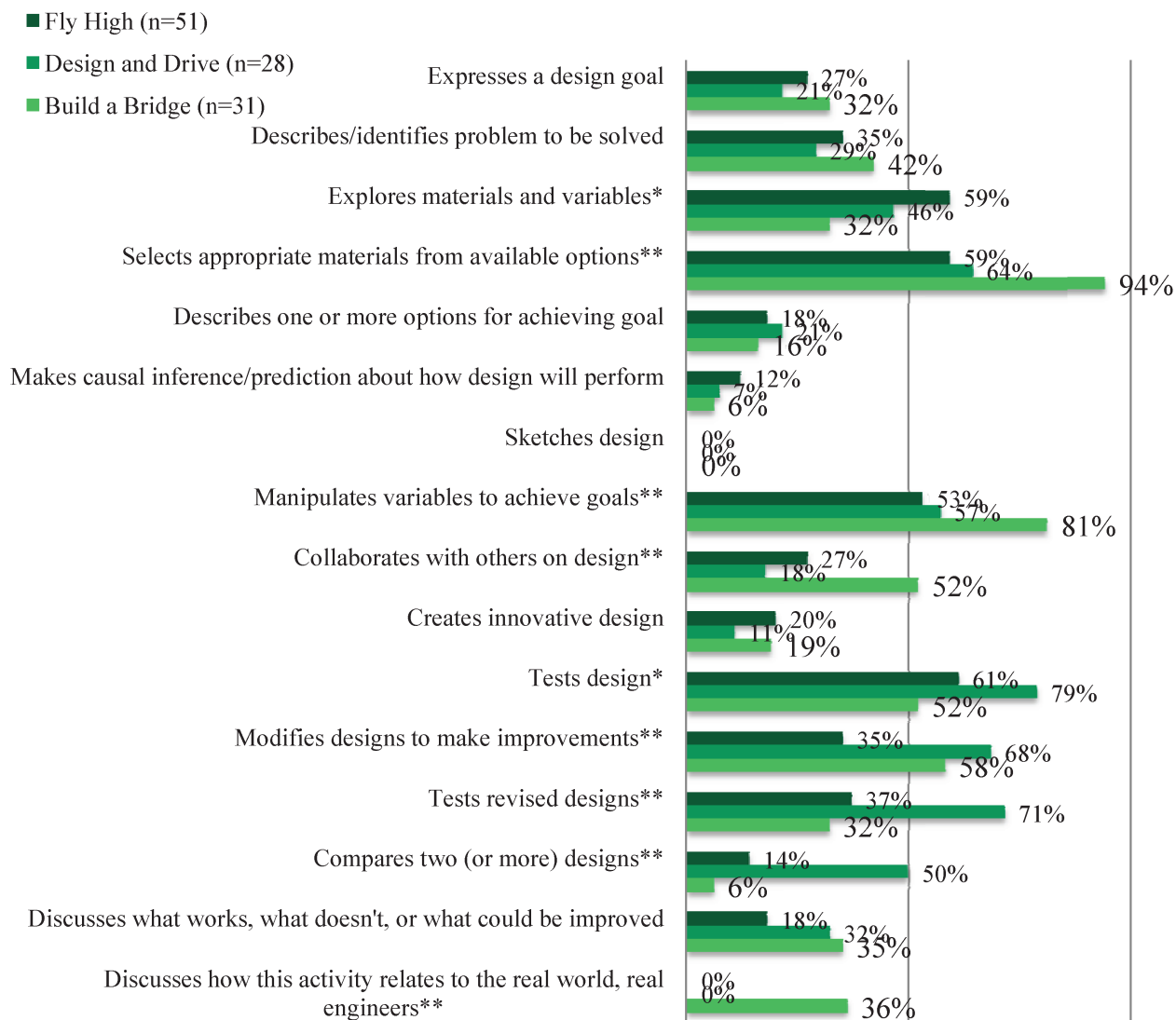Discusses how this activity relates to the real world, real engineers** — 0%, 0%, 36%

Figure 10. Engineering behaviors, by activity, as a percentage of observations. **Difference between activities is significant ($p < 0.05$). *Difference between activities is approaching significance ($p < 0.10$). Note: the last behavior, "Discusses how this activity relates to the real world, real engineers," was not collected for all data with $n = 14$ at *Fly High*, $n = 8$ at *Design and Drive*, and $n = 28$ at *Build a Bridge*.

unfacilitated (82%), while *Design and Drive* is slightly facilitated and *Build a Bridge* is more heavily facilitated. *Design and Drive* is observed to be unfacilitated in 47% of observations and introduction only in 40% of observations, and *Build a Bridge* is observed to be minimally to extensively facilitated in most of the observations (65%), as seen in Figure 13.

With regards to the design process, about half of the visitors in each activity fully completed the activity or went beyond what was expected, as can be seen in Figure 14. Many *Fly High* visitors fully completed the activity, but 35% only played with the materials by throwing them up into the wind tubes. *Design and Drive* visitors had the greatest completion rate, frequently modifying their wheel sizes and treads to optimize their cars; few only played with the materials by rolling just the wheels. Most *Build a Bridge* visitors either partially completed the activity by designing one iteration of a bridge without refinement or fully completed the activity by further refining their bridge.

Most visitors typically exhibited positive emotions as they engaged with the activities, with 77% of observed visitors showing intrigue/interest and 68% showing pleasure. Figure 15 shows a breakdown of affect by activity. Visitors at *Build a Bridge* more frequently showed confusion than those at other activities; however, these visitors also showed greater intrigue and interest through sustained focus.

Average Level of Behavior Reached (1=minimal, 3=extensive)

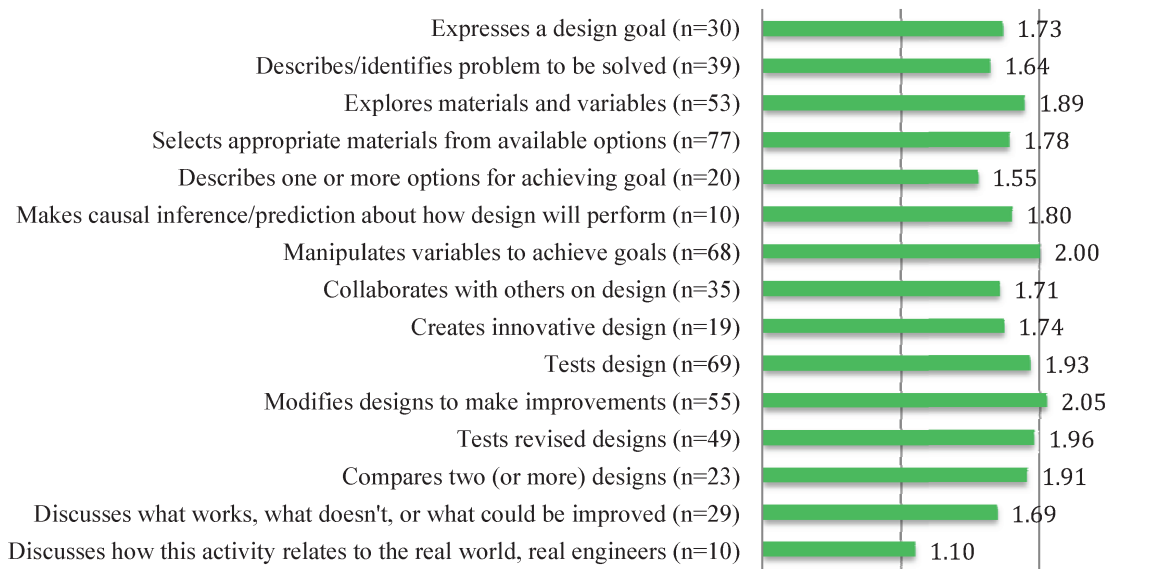| Behavior	Value
Expresses a design goal (n=30)	1.73
Describes/identifies problem to be solved (n=39)	1.64
Explores materials and variables (n=53)	1.89
Selects appropriate materials from available options (n=77)	1.78
Describes one or more options for achieving goal (n=20)	1.55
Makes causal inference/prediction about how design will perform (n=10)	1.80
Manipulates variables to achieve goals (n=68)	2.00
Collaborates with others on design (n=35)	1.71
Creates innovative design (n=19)	1.74
Tests design (n=69)	1.93
Modifies designs to make improvements (n=55)	2.05
Tests revised designs (n=49)	1.96
Compares two (or more) designs (n=23)	1.91
Discusses what works, what doesn't, or what could be improved (n=29)	1.69
Discusses how this activity relates to the real world, real engineers (n=10)	1.10

Figure 11. Average depth of behavior reached for visitors observed exhibiting behavior. Each behavior, if exhibited, was rated on a 1–3 scale (1 = the behavior was slightly exhibited, 2 = the behavior was moderately exhibited, 3 = the behavior was strongly exhibited).

On the other hand, visitors at *Fly High* most frequently showed excitement when testing items in the wind tubes. These visitors and those at *Design and Drive* also commonly showed pleasure when interacting at the exhibit.

Confirming the observed affect, all interviewed visitors indicated that the activity was either pretty fun (3) or very fun (4) on a four-point Likert scale (with a mean rating of 3.62), and most visitors reported that the activities were interesting (with a mean rating of 3.28 on a four-point Likert scale). In the interviews, visitors reported that they were attracted to the exhibit because it looked fun, something at the activity caught their eye, they liked building things, they saw their friends or other people doing the activity, or they had done the activity before and knew they liked it.

Activity properties and visitor behaviors

The three unique activities may have fostered certain visitor behaviors. Table 2 lists key properties of each activity, as well as significant observed visitor behaviors that are correlated with each activity.

Implications for exhibit design

We observed most children engaging in the basic steps of a design process, though there were quite a few who

only played with the manipulatives without creating a design. These observations are supported by the nature of the exhibit design. At *Fly High*, the open-ended environment, the availability and accessibility of manipulatives, and the unstructured format fostered the most common behaviors of selecting materials and testing, and thus of exploratory play in shorter interactions. However, there were children who stayed longer and exhibited behaviors related to building, testing, refining, and re-testing. These types of behaviors were also supported by the open-ended, but more structured and limited *engaging in and Drive* and *Build a Bridge* activities. Children at these activities had implicit (and sometimes explicit) goals and were often guided by facilitators. However, at all the activities, without direction or signage, it was difficult for children to identify a design goal and accordingly brainstorm solutions.

These activities engaged visitors for extended periods of time. We note that the long duration at the exhibit may be due to the fact that the exhibit is located near the front of the museum, where most visitors begin their visit. Prior research has shown that visitors tend to spend more time at earlier exhibits than at later ones (Serrell, 1997). Nonetheless, the much longer duration of 12–22 minutes (and maximum of 75 minutes) spent at individual activities in *Ingenuity in Action* in comparison to the average time of one to three minutes at other exhibits in museums (Diamond, 1986; Randol, 2005) is encouraging. The high engagement levels and positive affect displayed indicate that the exhibit is fun for children, likely contributing to their choice to stay at the exhibit for an extended period of time. Furthermore, to complete fully and gain the most out of the type of activities at this exhibit, children need to devote a significant amount of time to the process.
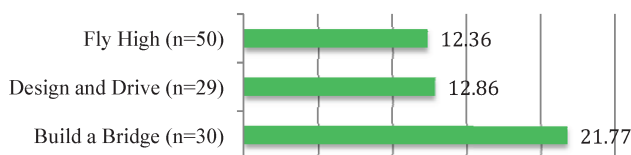
Average Time Spent [min.] (p=0.003)

Activity	Value
Fly High (n=50)	12.36
Design and Drive (n=29)	12.86
Build a Bridge (n=30)	21.77

Figure 12. Average time spent, by activity.
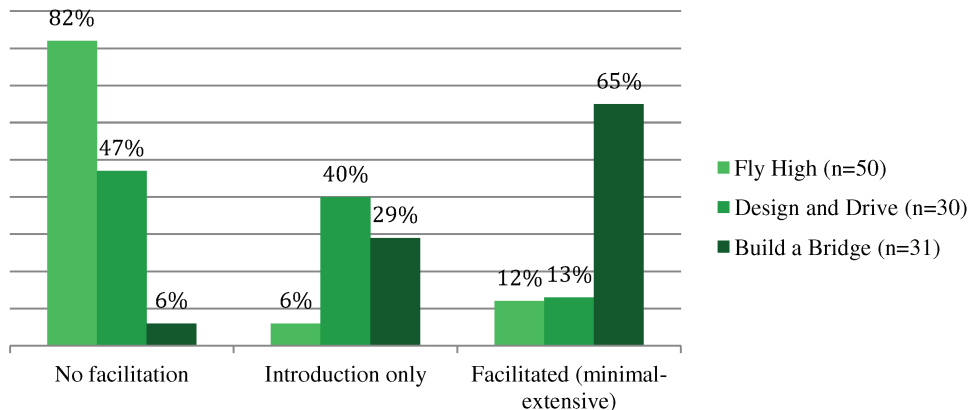
Facilitation Level (by activity) (p<0.001)

Figure 13. Observed facilitation level, by activity. Minimal and extensive facilitation were combined because of the small sample size ($n = 6$) of extensively facilitated interactions. (No facilitation = No interaction between facilitator and visitor. Introduction only = Facilitator provides an introduction to the activity and visitor completes it on their own. Minimal = Facilitator provides minimal facilitation (answers visitor questions, offers minor suggestions). Extensive = Facilitator provides extensive facilitation (guides visitor through process, engages in extended dialogue with visitor).)

From the interviews, we infer that in a successful engineering exhibit, designers must first attract visitors with something that catches their attention. In addition, if visitors are at the activity, other visitors must be able to see appropriate building and designing behaviors they can imitate. Children's indication of their interest in building things implies that the availability of variables and materials fostered their desire to design and build. Finally, the returning children (as reported in interviews; e.g., "I've been here before") portray to us the importance of the value of replay in exhibit design, where children can return to the exhibit regularly and continue an extended learning experience. The extended learning experience is

especially important for an engineering exhibit as it can promote the connection of the experience to the real world and to real engineers.

To what extent are visitors aware of the activities' connection to engineering?

In our observations, visitors rarely discussed the exhibit's connection to the real world and real engineers. Only visitors at *Build a Bridge* did so (though only about half of our observations included this data, most of which were collected at this activity). Additionally, our interviews revealed that a large number of visitors were not able to

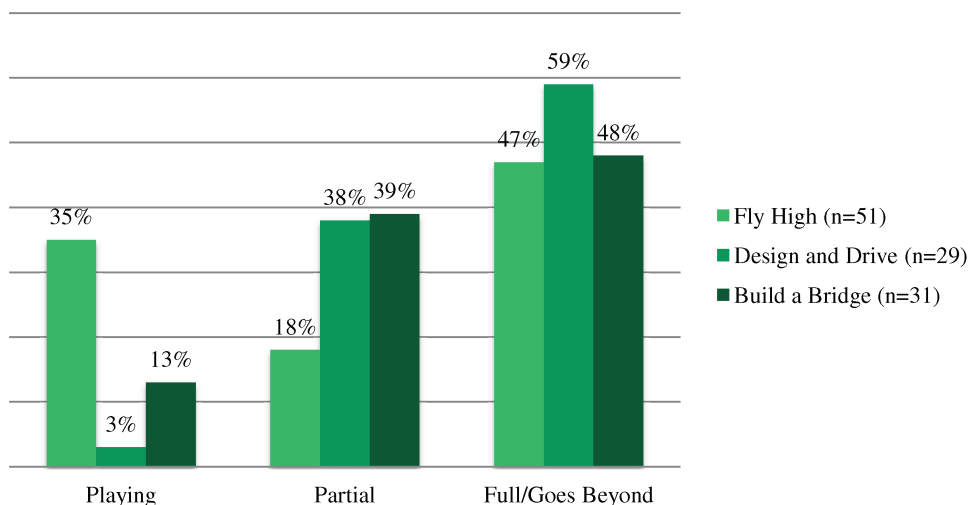**Activity Completion Level (by activity) (p=0.005)**

Figure 14. Activity completion of visitors, by activity. Full Completion and Goes Beyond Activity were combined because of the small sample size ($n = 10$) of groups who exhibited Goes Beyond Activity. ($p = 0.005$; Playing = Visitor plays with the manipulatives, but does not do the activity as intended. Partial Completion=Visitor partially completes the activity. Full Completion = Visitor fully completes the activity. Goes Beyond Activity=Visitor completes activity and takes it further.)
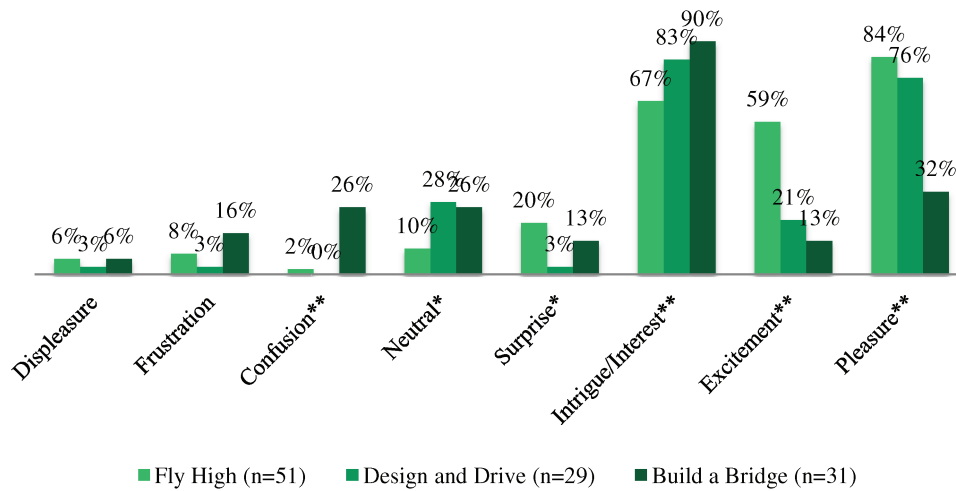
Affect (by activity) (**p<0.05, *p<0.10)

Figure 15. Affect observed in visitors, by activity. **Difference between activities is significant ($p < 0.05$) *Difference between activities is approaching significance ($p < 0.10$).

identify the activities' connection to a real occupation (in particular, engineering), especially at *Fly High* (see Figure 16). When asked who does this activity in the real world, only 5% of *Fly High* and 35% of *Design and Drive* visitors indicated an engineer, architect, or designer, while all interviewed visitors at *Build a Bridge* indicated either people who make things or engineers, designers, or architects. When asked what they learned, visitors reported

Table 2

Activity properties and observed behaviors. Most frequently exhibited characteristics are marked **bold** if $p < 0.05$ and *italicized* if $p < 0.10$ (with significant difference between activities)

	Fly High	Design and Drive	Build a Bridge
Properties			
Setting	Two wind tubes along with bins to hold materials are easily accessible to any passersby	Area is fenced off with one entrance/exit; cars are distributed by facilitators, wheels are accessible in bins, and ramps are open to all inside the area	One table (seats about 8) is designated for building bridges, which is monitored by a facilitator
Variables	Design is made from scratch or adopted/modified from previous visitors' designs; variables include consumable materials like binder clips, cups, plates, pipe cleaners, paper, pool noodles	Cars chasses are pre-made; variables include wheel sizes and treads and ramp construction and surfaces	Bridges are made from scratch or adopted/modified from previous designs; variables include four types of construction elements (two types of rods, hub, cable)
Testing	Visitors place an item into the wind tube to see if it flies vertically	Visitors turn on the motorized car to see if it can traverse the ramps	Visitors apply forces at various points on the bridge and/or test whether toy cars can traverse the bridge
Facilitation	Unfacilitated (82%)	Introduction (40%)/unfacilitated (47%)	Facilitated (65%)
Time [min.]	12.36	12.86	21.77
Activity completion	Playing (35%)/full (47%)	Partial (38%)/full (59%)	Partial (39%)/full (48%)
Most common engineering behaviors	Selects appropriate materials (59%)	Selects appropriate materials (62%)	**Selects appropriate materials (94%)**
	Explores materials (59%)	Manipulates variables (55%)	**Manipulates variables (81%)**
	Manipulates variables (53%)	Tests design (76%)	**Collaborates (52%)**
	Tests design (61%)	**Modifies design (66%)**	Modifies design (58%)
		Tests revised design (69%)	**Makes connection to real world (36%)**
		Compares two or more designs (48%)	
Most common affect	Intrigue/interest (67%)	Intrigue/interest (83%)	**Intrigue/interest (90%)**
	Excitement (59%)	Excitement (21%)	**Confusion (26%)**
	Surprise (20%)	Pleasure (76%)	Pleasure (32%)
	Pleasure (84%)	**Neutral (28%)**	Neutral (26%)

Who does this in the real world? (p=0.006)

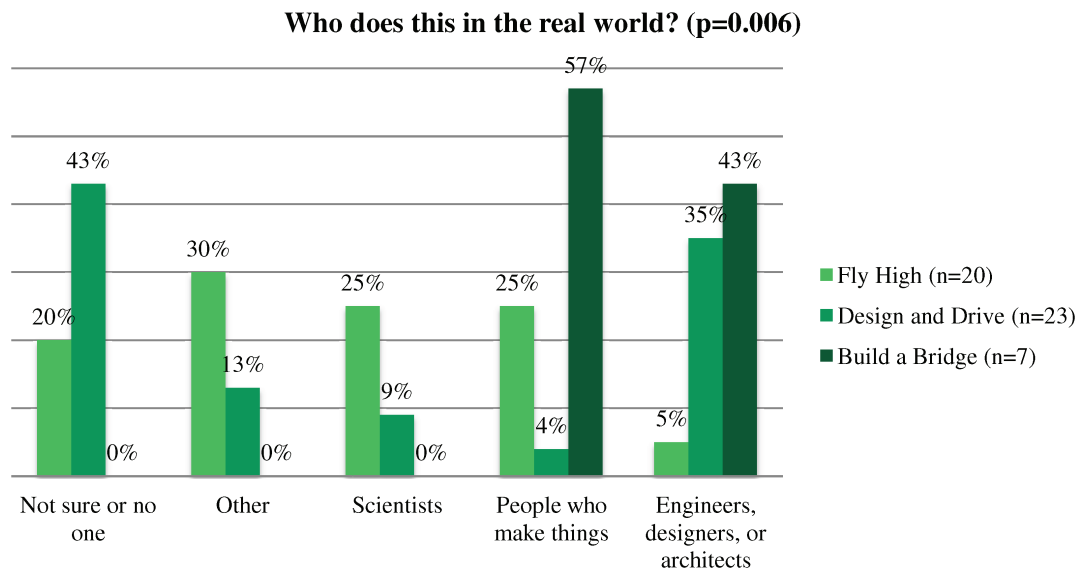Figure 16. Visitor answers to the interview question "Who does this in the real world?" ($p = 0.006$). Note that some visitors named more than one person, so percentages do not total 100%.

specific science and technical concepts related to the specific activities and other concepts related to the process of design (e.g., problem-solving, refining, whether something works or not), but nothing related to engineering fields. For instance, at *Fly High*, visitors frequently discussed which designs would fly or not, or how weight slows down flying objects; at *Design and Drive*, visitors discussed which wheels work best on which surfaces; and at *Build a Bridge*, visitors discussed the weak and strong points on bridges.

Implications for exhibit design

The more explicit connection to the real world at *Build a Bridge* could be attributed to the more obvious connection to real bridges, especially local well-known (and visible from the museum) bridges like the San Francisco-Oakland Bay Bridge and the Golden Gate Bridge. The more extensive facilitation also gave more opportunities for the staff to discuss real-world connections.

As no signs at the exhibit indicated anything explicitly related to engineering, the findings showing a lack of connection to engineering are not a surprise. If parents and adults accompanying children do not realize the exhibit is about engineering, it is unlikely that children will make the connection. Furthermore, the general lack of public under-standing about engineering (NAE, 2008) intensifies this issue. Thus, if we aim to teach the public and children about engineering, it is important for us to make more explicit connections to engineering and the real world, potentially through clearer signage and more extensive facilitation.

How does collaboration correlate with engineering behaviors exhibited?

We found that visitors who exhibited collaboration with other visitors also exhibited more engineering behaviors overall. Visitor groups who collaborated exhibited an average of 6.26 behaviors out of 14 (excluding the "collaborates" behavior), versus visitors who did not collaborate who exhibited an average of 4.29 behaviors (see Figure 17a). When controlling for activity, we found the differences to be significant ($p < 0.001$). Furthermore, we found that the highest average level of all engineering behaviors for visitors who collaborated was 2.40 on a scale of 1–3, greater than the average of 2.04 for visitors who did not collaborate (see Figure 17b). Again, controlling for activity, we found the differences to be still significant ($p = 0.005$). In other words, visitors who collaborated exhibited engineering behaviors much more strongly than those who did not collaborate.

We also found that the average time spent by visitors who collaborate to be 23 minutes, more than double the average of 11 minutes spent by visitors who did not collaborate (see Figure 18). This was still found to be significant ($p < 0.001$) when controlling for activity. Finally, we observed greater activity completion in groups that collaborated (see Figure 19). Sixty-three percent (63%) of groups who collaborated fully completed the activity or went beyond what was expected, compared to only 44% of groups who did not collaborate. This was also found to be significant ($p = 0.002$) when controlling for activity.

Implications for exhibit design

Our findings indicate that these activities did not always elicit collaboration. However, groups that did collaborate exhibited more engineering behaviors, reached greater depths of engineering behaviors, spent much more time at the exhibit, and completed the activity more fully. Consistent with these findings, collaboration is commonly included as a component of engineering education (e.g., Committee on K-12 Engineering Education, 2009;

Average Number of Behaviors Exhibited (not including collaborates) (by collaboration) (p = 0.001)
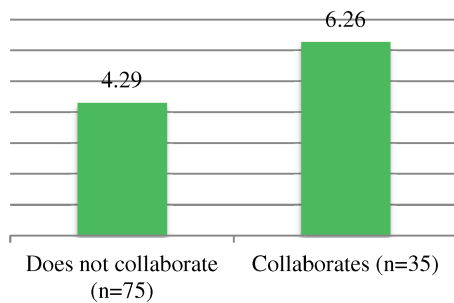
Highest Level of Behavior Reached (by collaboration) (p = 0.004)

(a)
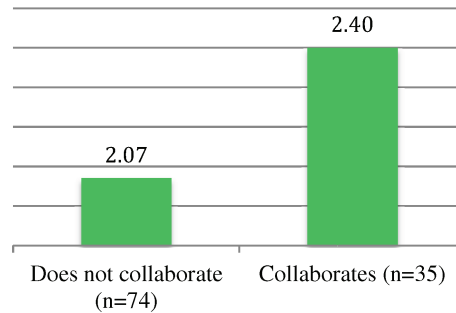
(b)

Figure 17. The average number of engineering behaviors exhibited out of 14 behaviors (a) and the highest level of behavior reached on scale from 1–3 (b) by collaboration.

Engineering Accreditation Commission, 2009). We therefore believe that designing for collaboration may be another important key for success in designing for engineering learning, as abilities to function in teams and to collaborate are fundamental for successful engineers. We also note that visitors at *Build a Bridge* engaged in collaboration more frequently and also exhibited more engineering behaviors. Thus, it is important to design the exhibit such that it encourages collaboration, and possibly even requires collaboration, in order for visitors to participate.

What are the best kinds of facilitation for optimizing encounters with engineering thinking?

Overall, we found that more extensive facilitation correlates with an increase in time spent at the exhibit, increase in activity completion, higher engagement levels, increase in behaviors exhibited, and a higher level of behaviors reached. These correlations with facilitation were still significant at a 5% level when controlling for activity.

In coding the observation data, facilitation was divided into the following categories: (a) No interaction between facilitator and visitor; (b) Facilitator provides an introduction to the activity and visitor completes it on his own; (c) Facilitator provides minimal facilitation (answers visitor questions, offers minor suggestion); and (d) Facilitator provides extensive facilitation (guides visitor through process, engages in extended dialogue with visitor). Because there were very few instances of extensive facilitation—a total of six observations—this category was combined with minimal facilitation.

We found that with minimal to extensive facilitation, the average time spent was 26 minutes, as opposed to the average of 11 minutes for groups with introduction only from the facilitator or no facilitation (see Figure 20). When controlling for activity, we found the increase in time spent to be still significant ($p < 0.001$). Furthermore, minimal to

Average Time Spent [min.] (by collaboration) (p < 0.001)
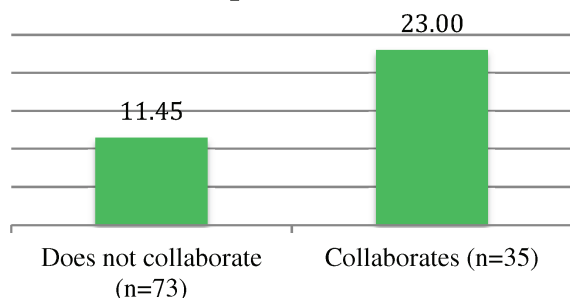
Figure 18. Average time spent by collaboration.

Activity Completion (by collaboration) (p = 0.006)

■ Does not collaborate (n=75)   ■ Collaborates (n=35)

Figure 19. Activity completion by collaboration. (Playing = Visitor plays with the manipulatives, but does not do the activity as intended. Partial Completion = Visitor partially completes the activity. Full Completion = Visitor fully completes the activity. Goes Beyond Activity = Visitor completes activity and takes it further).

Average Time Spent [min.] (by facilitation level)
(p < 0.001)

No facilitation (n=56)   11.41
Introduction only (n=23)   11.26
Facilitated (minimal-extensive; n=29)   25.62

Figure 20. Average time spent by facilitation level.
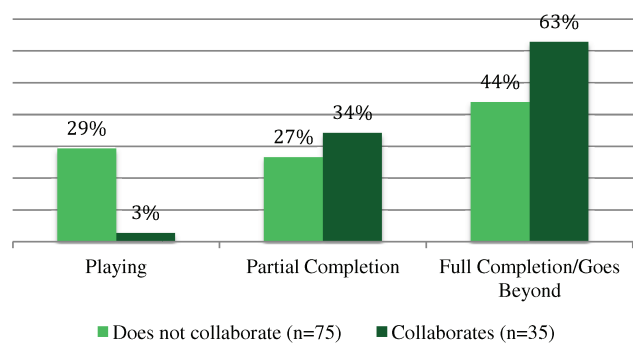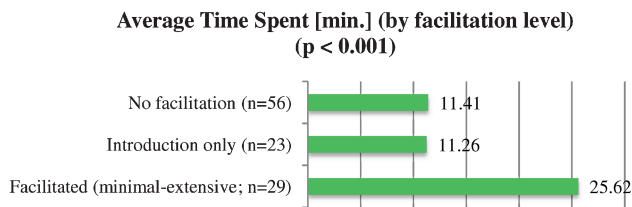
extensive facilitated groups were more likely to complete the activity fully the activity than those with no facilitation (see Figure 21). This is also significant when controlling for activity ($p = 0.005$). Finally, minimal to extensive facilitated groups were more likely to exhibit interest/intrigue ($p < 0.05$) as well as more confusion ($p < 0.05$), possibly because these visitors had a goal, an indicator of success or failure. Only the increased interest/intrigue was significant when controlling for activity ($p = 0.052$).

Facilitated groups also exhibited significantly more engineering behaviors than non-facilitated groups, as shown in Figure 22. Minimal to extensive facilitated groups exhibited an average of 7.03 behaviors, whereas introduction only groups exhibited 4.58 and no facilitation groups exhibited 4.56 behaviors. The differences are even more dramatic when controlling for activity ($p < 0.001$). Minimal to extensive facilitated groups were also more likely to exhibit all engineering behaviors except "explores materials and variables" and "compares two or more designs" (see Figure 23). Unfacilitated groups were significantly more likely to exhibit "explores materials and variables." However, the behavior "explores materials and variables" was explicitly coded for visitors who played without creating a design while it is desirable to have visitors create a design in addition to playing with materials. The difference between groups for "compares

two or more designs" is not significant at the 10% level. Additionally, facilitated groups reached higher levels of engineering behaviors than did other groups (see Figure 24). When controlling for activity, this was still significant ($p = 0.017$).

From the interviews, there was no significant difference for how fun or interesting visitors found activities between groups with more or less facilitation. Thus, facilitation appears to have no correlation with fun and interest, but it is significantly correlated with visitor participation in engineering behaviors and design processes.

Overall, facilitated groups constituted only 27% of observed groups, and extensively-facilitated groups constituted only 6%. However, anecdotally, more extensive facilitation appears better than minimal facilitation. These groups exhibited more behaviors concerning identifying problems, brainstorming solutions, and communicating results, and exhibited more engineering behaviors overall.

Facilitation and exhibit design

Facilitation may play a significant role in enhancing children's experience of the activity. It correlates with an increase in the amount of time engaged in the activity, an increase in the likelihood of fully completing the activity, higher engagement levels, an increase in the number of engineering behaviors exhibited, and a higher level of behavior reached; facilitated groups were also more likely to exhibit certain behaviors and to go deeper in certain behaviors. These findings support the findings of Schauble et al. (2002), in which they compared staff facilitation of exhibits to parent facilitation. Schauble et al. found that the staff used a variety of ways to help children learn through appropriate questions and explanations, whereas parents focused more on logistical forms of help. Results in our study indicate that facilitation levels 3 and 4—minimal

Activity Completion (by facilitation level)
(p < 0.001)

Playing: 34%, 4%, 10%
Partial Completion: 20%, 58%, 23%
Full Completion/Goes Beyond: 46%, 38%, 67%

■ No facilitation (n=56)
■ Introduction only (n=24)
■ Facilitated (minimal-extensive) (n=30)
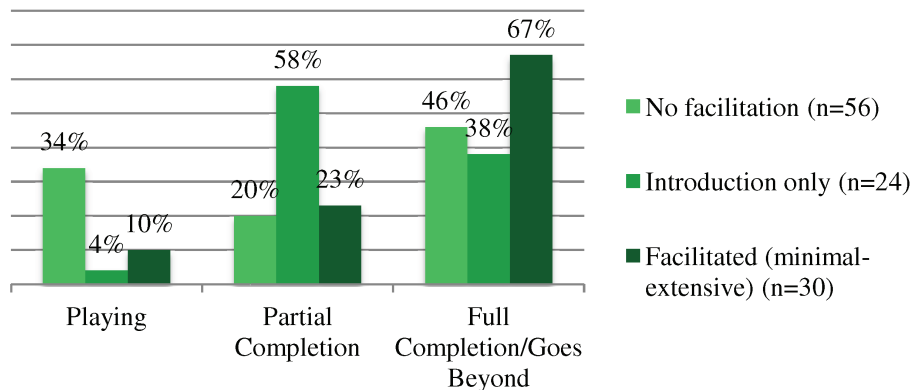
Figure 21. Activity completion by facilitation level. Full Completion and Goes Beyond Activity were combined because of the small sample size ($n = 10$) of groups who exhibited Goes Beyond Activity. (Playing = Visitor plays with the manipulatives, but does not do the activity as intended. Partial Completion=Visitor partially completes the activity. Full Completion = Visitor fully completes the activity. Goes Beyond Activity = Visitor completes activity and takes it further).

Average Number of Behaviors Exhibited (by facilitation level) (p = 0.001)

No facilitation (n=55)	4.56
Introduction only (n=24)	4.58
Facilitated (minimal-extensive) (n=30)	7.03

Figure 22. Average number of behaviors exhibited out of 15 behaviors by facilitation.

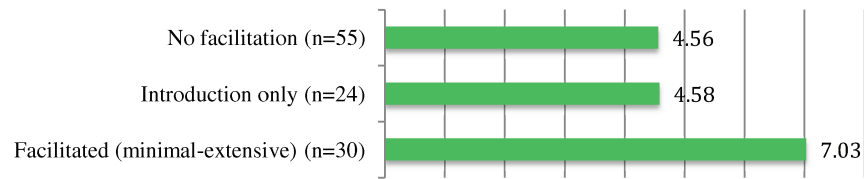facilitation through answering visitor questions and offering minor suggestions and extensive facilitation through closely guiding visitors through the process and engaging in extended dialogue with the visitor—may be more effective at engaging visitors in engineering behaviors. Thus, it is important to consider how to appropriately train facilitators and staff at the exhibit to foster visitors' engineering habits of mind.

Engineering Behaviors (by facilitation level) (**p < 0.05, *p < 0.10)

Behavior	No facilitation (n=55)	Introduction only (n=24)	Facilitated (minimal-extensive) (n=30)
Expresses a design goal	24%	21%	37%
Describes/identifies problem to be solved**	24%	29%	63%
Explores materials and variables**	60%	46%	27%
Selects appropriate materials from available options*	64%	67%	87%
Describes one or more options for achieving goal	15%	13%	30%
Makes causal inference/prediction about how design will perform**	5%	0%	20%
Sketches design	0%	0%	0%
Manipulates variables to achieve goals**	53%	58%	83%
Collaborates with others on design**	22%	29%	53%
Creates innovative design	16%	8%	23%
Tests design	60%	58%	73%
Modifies designs to make improvements**	38%	42%	80%
Tests revised designs	42%	33%	60%
Compares two (or more) designs	20%	29%	17%
Discusses what works, what doesn't, or what could be improved**	15%	25%	50%
Discusses how this activity relates to the real world, real engineers**	0%	14%	45%

■ No facilitation (n=55) ■ Introduction only (n=24) ■ Facilitated (minimal-extensive) (n=30)
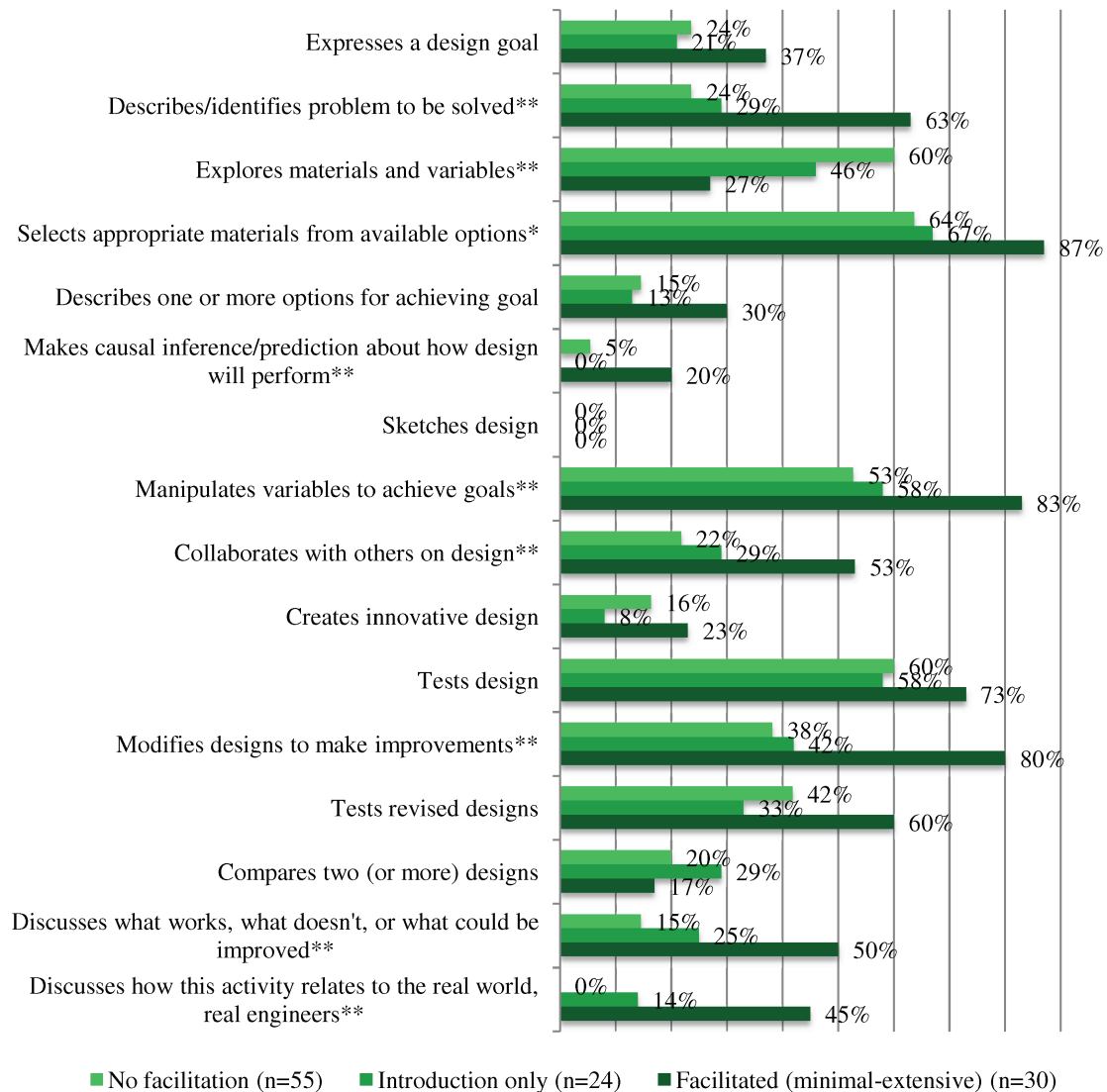
Figure 23. Engineering behaviors exhibited by level of facilitation. Note: the last behavior, "Discusses how this activity relates to the real world, real engineers," was not included in all observations with $n = 20$ for facilitated groups, $n = 7$ for introduction only, and $n = 23$ for no facilitation.

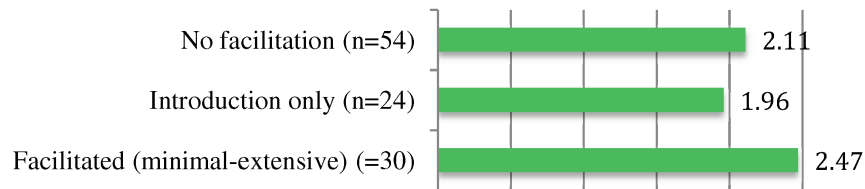## Highest Level of Behavior Reached (by facilitation level) (p = 0.002)

Figure 24. Highest level of behavior reached (on a scale of 1–3) by level of facilitation.

Discussion

The *Ingenuity in Action* exhibit offers a framework for designing for engineering learning. Open-ended tasks provide visitors the unique opportunity to solve complex problems, thereby giving them experience with real challenges and involving them in engineering design thinking through tinkering, a naturally elicited design process. Furthermore, the exhibit is highly successful in engaging visitors in engineering behaviors, as confirmed by the findings from our observations and interviews. All but one observed group exhibited engineering behaviors. However, the one group that did not exhibit engineering behaviors merely watched the activity without actively engaging. Thus, tinkering with manipulatives in an open-ended design-based activity involves visitors acting like engineers.

We also noted differences in behaviors between activities, with more playing at *Fly High*, more testing at *Design and Drive*, and more building at *Build a Bridge*. These differences could be attributed to the differences in facilitation as well as the differences in activity design and environment. The nature of each of these activities also forced facilitation strategy; if the activity was safe for visitors and easy to figure out, less facilitation was implemented, and if it was complex or potentially unsafe, more facilitation was implemented. *Fly High* had more impressive and quick feedback in testing flying things, was more open-ended and less constrained by materials, was easily accessible to passersby, and was rarely facilitated because of its ease of use; visitors at *Fly High* stayed the shortest amount of time, engaged mostly in exploratory play and testing, and showed the greatest excitement and surprise, possibly because of the impressive feedback and lesser facilitation, as well as the ease of passing through and interacting without creating a design. *Design and Drive* involved partially pre-built car designs, was more constrained in the variables (wheels and ramps), and facilitators usually only introduced visitors to how to turn the cars on without extended involvement; here, visitors engaged in more testing, refining, and comparing all possible designs, stayed only slightly longer than *Fly High* visitors, and showed neutral affect as they followed cars around the exhibit, possibly because of the limited amount

of variables and the limited facilitation. *Build a Bridge* was the most intimate setting, had a facilitator constantly present and active because of its more complex activity and potential choking hazard for small children, and was constrained to four types of basic building components; visitors at *Build a Bridge* stayed for significantly longer, engaged more in carefully planning and building their designs, collaborated more frequently, and made more connections to the real world, possibly because of its more intimate and facilitated structure, the constrained variables, and the obvious connection to real world bridges and more familiar engineers. These visitors also showed the most confusion and intrigue/interest as the activity was more complex, but its complexity and the more extended facilitation may have also sustained them for longer times.

Additionally, we found that collaboration and facilitation each correlated with an increase in time spent at the activity, increase in engineering behaviors exhibited, greater depth of engineering behavior reached, and fuller activity completion. The benefits associated with collaborating may be partially a result of more observable, and thus more measureable, external dialogue. However, as mentioned earlier, collaboration with peers and adults has been found to improve learning (Cohen, 1994; Vygotsky, 1978). Furthermore, teamwork and collaboration are key features of the profession of engineering that allow for diverse contributions to solutions. We believe that collaboration may have sustained engagement and elicited more engineering behaviors as the participants built actions and ideas off of one another and discussed the goings-on of the exhibit. The benefits associated with facilitation may be due to the guided structure it provided, helping visitors engage in appropriate behavior and actions. Furthermore, facilitation through the use of just-in-time guidance may prevent the learner from giving up or participating aimlessly (Kali, Fortus, & Ronen-Furhman, 2009). Thus, without the constraints of instructions or directed actions, the lack of facilitation at *Fly High* may have resulted in more exploratory play behaviors and shorter stay times compared to the other two activities.

On the other hand, we do note that, in general, engineering behaviors associated with identifying, brainstorming, and communicating were less frequently observed, while visitors more frequently exhibited

behaviors associated with building, testing, and refining. We also found in our observations that few visitors related their involvement in the exhibit to the real world and to real engineers, and interviews revealed few visitors who identified engineers as people who participated in similar activities in their jobs.

Proposed exhibit improvements

Further research is needed, but we hypothesize that some of the negative findings may be mitigated with more extensive facilitation and structure. In support of this hypothesis, Rennie and McClafferty (1993) studied play at an interactive exhibit, and showed that children who engaged in investigatory rather than fantasy play were more likely to learn the science concepts of the exhibit. At *Ingenuity in Action*, fantasy play can be thought of as partial completion of the activity, where the visitor only plays with the manipulatives and does not create a design. Investigatory play, on the other hand, involves play in experimenting and investigating designs that do and do not work. We seek to support investigatory play at the exhibit. Scaffolding and guided inquiry are noted as successful teaching methods to loosely structure investigatory learning (Linn, Davis, & Eylon, 2004; White, Frederiksen, & Collins, 2009). Thus, we propose more explicit guidance and structure through (a) facilitators that are always present who offer introductions to the exhibit, present possible goals and challenges, and provide ongoing feedback on visitors' design performances and (b) clear and upfront signage that provides a diagram of an engineering design process to follow and presents a challenge of the day with a scoreboard and examples of top designs.

We also believe that fostering collaboration at the exhibit can increase engagement as well as more profound and productive participation in engineering-related behaviors. Our findings at this exhibit show that collaboration correlates with increases in time spent, engineering behaviors exhibited, and activity completion. Consequently, promoting and providing for collaboration at the exhibit may enhance productive engineering behaviors. We propose fostering collaboration through challenges that require more than one person and are appealing to all ages, signage that promotes working on teams, and facilitation asking parents and children to collaborate.

In addition, providing context and an explicit connection to real-world engineering would help visitors become more aware of the field of engineering, as our findings on the lack of connection to engineering is of particular concern. Anderson, Piscitelli, Weier, Everett, and Tayler (2002) state that museum experiences that specify context "will provide greater impact and meaning than [those] that are decontextualized in nature." Framing learning contexts in relation to a larger, more meaningful context (in this case, engineering in the world) may also increase impact and

deepen learning (Engle, 2006). Our proposal for making the connection more explicit is to (a) train facilitators to make connections to related engineered objects from the real world, especially those relevant to the visitors, and discuss how engineers use the same processes to improve designs and (b) provide signage that shows images of related engineered objects and explains relevant science and engineering concepts.

How do we design our environment to make the connection to engineering more explicit? As a next step, we seek to explore the above modifications to the exhibit design, including signage and facilitation that may help reinforce the connection to engineering. Further questions that will guide us in our design modification include: How do we better elicit engineering behaviors related to identifying problems and goals, brainstorming solutions, and communicating results?, How can we design to foster more collaboration?, and Are there alternatives to facilitation that are just as effective in eliciting engineering behaviors?

Limitations

These findings are limited by the nature of the observations, in which the researcher cannot probe internal cognitive processes. Because children are not necessarily articulating every thought they have, we hypothesize that much of the identifying (step 1) and brainstorming (step 2) was done internally, where the visitor has a goal and a problem to solve in mind. Oftentimes, visitors only articulated their goals when they collaborated in groups, consistent with studies in which students working in groups (as opposed to individually) explained their thoughts and reasonings to each other (e.g., Mercer, 2008; Okada & Simon, 1997). For step 2, the actions that were observable are "explores materials and variables" and "selects appropriate materials from available options," and consequently, these may have been observed more frequently than the other behaviors of step 2. The only other observable action, "sketches design," was never observed because the exhibit was not designed to elicit this behavior, particularly as there were no pencils or sketching paper for visitors to use nor any directives in this respect. On the other hand, we were able to probe some internal motivations and perceptions in the post-observation interview. However, because interviews occurred after participation in the activity, internal thoughts during activity engagement were not probed.

The findings for the behavior "Discusses how this activity relates to the real world, real engineers" is also limited by the observations conducted. Only about half the observations included this data, most of which were conducted at *Build a Bridge* ($n = 28$) and fewer were conducted at the other activities *Design and Drive* ($n = 8$) and *Fly High* ($n = 14$). However, the interviews reveal that visitors at *Build a Bridge* also more frequently identified

engineers and people who make things as doing similar activities.

Another limitation involved interviewing children. When asking children questions, it is sometimes difficult to distinguish whether the child is answering how he believes he should answer an adult or answering honestly. There are some techniques that we used for interviewing children: asking simpler yes or no questions, not asking too many questions, standing at the child's height, using props (the exhibit), and interacting with children in a natural site (Brenner, 2006; Siegal, 1991). Even with these techniques, we can only assume that the child answered honestly and consider these results best-case scenarios.

Finally, there may have been self-selection bias of visitors who agreed to stay for interviews rather than moving on to the next exhibit. Because the exhibit was located at the front of the museum, visitors had either just entered or were about to leave the museum. Most visitors who refused the interviews often reasoned that they did not have enough time (mostly because their parking ticket was expiring and they were on their way out). In reviewing these data, future researchers should take into account these limitations.

Conclusion

Through observations and interviews of 112 groups at the *Ingenuity in Action* exhibit, we found that children engaged in engineering habits of mind through tinkering in an open-ended exhibit. Furthermore, collaboration and facilitation correlated with deeper and more engineering behaviors exhibited and longer stay times. However, children are mostly unaware of the exhibit's connection to engineering. We believe that with further structure and contextualization, the exhibit can make a more explicit connection to the real world of engineering and can channel children's natural tendency to tinker and explore in order to promote even deeper levels of engineering behaviors. Our findings show that the *Ingenuity in Action* exhibit establishes a framework of designing for engineering learning. Engineering exhibits should:

1. be open-ended to allow for a variety of possible solutions;
2. offer materials with which visitors can create a unique design and that can be used in a variety of ways;
3. provide a test to determine the success of the design;
4. be accessible for all ages and genders;
5. allow for collaboration;
6. use facilitation to provide explicit engineering goals, feedback to visitors, and connections to engineering; and
7. include clear signage and examples of engineering.

Other informal and formal learning environments can build on these findings to foster children's predispositions to engineer.

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APPENDIX A: OBSERVATION PROTOCOL

INGENUITY LAB OBSERVATION PROTOCOL

Date:	Activity:		Facilitator:		
	Number in group:	**Group Type:**		School	Family
Age and Gender:	<7 8–12	13–17 18–21	22–35 36–50	50+	
START TIME:		END TIME:	OBSERVER		

Activity Completion

1. Playing. Visitor plays with the manipulatives, but does not do the activity as intended.
2. Partial Completion. Visitor partially completes the activity.
3. Full Completion. Visitor fully completes the activity.
4. Goes Beyond Activity. Visitors completes activity and takes it further.

Level of Engagement

1. Low. Visitor makes cursory stop with minimal engagement with activities (e.g. sitting down, talking with facilitator &/or quickly touch manipulatives).
2. Moderate, low. Visitor engages with facilitator or focuses on activities, but with low interest (e.g. tries the activity, but may not complete).
3. Moderate, high. Visitor engages with facilitator or activity, but with medium interest (e.g. "goes through the motion" to do activity, but does not take further).
4. High. Visitor fully engaged with facilitator &/or activities (e.g. dem onstrates prolonged engagement with the activity, appearance of directed focus or discussion related to activity, actively completes the activity, repeats it multiple times or does related activity).

Level of Facilitation

1. No interaction between facilitator and visitor
2. Facilitator provides an introduction to the activity and visitor completes it on their own
3. Facilitator provides minimal facilitation (answers visitor questions, offers minor suggestions)

4. Facilitator provides extensive facilitation (guides visitor through process, engages in extended dialogue with visitor)

Affect

(Which of the following emotions, if any, do visitors show as they participate in the activity? Check all that apply. Please note your observations & impressions.

a. displeasure   _____
b. frustration   _____
c. confusion   _____
d. neutral   _____
e. surprise   _____
f. intrigue/interest   _____
g. excitement   _____
h. pleasure   _____

Behavior	(−,√,+)	Indicate if facilitator initiated
Describes/identifies a problem to be solved (finding flaws)		
Expresses a design goal ("I want it to…")		
Describes one or more options for achieving goal (brainstorming)		
Sketches design		
Selects appropriate materials from available options		
Makes causal inference/predictions about how design will perform		
Explores materials and variables (without designing)		
Manipulates variables to achieve goal (building, creating)		
Collaborates with others on design		
Creates innovative design (creates unusual design compared to typical designs by visitors)		
Tests design		
Modifies design to make improvements		
Tests revised design		
Compares two (or more) designs		
Discusses what works, what doesn't, or what could be improved		
Discuss how this activity relates to the real world, real engineers, etc.		

NOTES:

APPENDIX B: INTERVIEW PROTOCOL

Script: *Hi, my name is _____. We are talking to people to find out what they thought about these activities. Could I ask you a few questions? This will take about five minutes. You can stop at any time.*

1) What attracted you to this activity? Why did you want to try it?
2) What was this activity about? Did you learn anything new at this activity?
3) What did you do at this activity? Tell me a little about the steps you went through.
4) Do you think that people do this in the real world? Who might do this? (IF VISITOR NEEDS TO LEAVE, SKIP THESE QUESTIONS)
5) Was there anything confusing or frustrating about this activity?
6) How fun was the activity?

Not at all fun	A little fun	Pretty fun	Very fun
O	O	O	O

7) How interesting was the activity?

Not at all interesting	A little interesting	Pretty interesting	Very interesting
O	O	O	O

8) What could we do to improve the activity (make it more fun or interesting)?