Light It Up: Using Paper Circuitry to Enhance Low-Fidelity Paper Prototypes for Children

Anneli Hershman*
MIT Media Lab
Cambridge, MA, USA
anneli@media.mit.edu

Juliana Nazare*
MIT Media Lab
Cambridge, MA, USA
juliana@media.mit.edu

Jie Qi*
MIT Media Lab
Cambridge, MA, USA
jieqi@media.mit.edu

Martin Saveski
MIT Media Lab
Cambridge, MA, USA
msaveski@media.mit.edu

Deb Roy
MIT Media Lab
Cambridge, MA, USA
dkroy@media.mit.edu

Mitchel Resnick
MIT Media Lab
Cambridge, MA, USA
mres@media.mit.edu

ABSTRACT

Paper prototyping is an important tool for designing and testing early technologies during development. However, children have different relationships with technology and thus one cannot expect children to assess paper prototypes with the same mental model as adults. In this paper, we examine the effect of incorporating paper circuitry into low-fidelity paper prototypes, in order to add a level of interactivity that is not present in traditional paper prototypes. We conducted a study with 20 children ages 3 to 10 years old where participants used a cardboard prototype of a voice-controlled rocket on a pretend play mission to Mars. Children chose between buttons that lit up when pressed using paper circuitry, and buttons that did not light up, and explained their selections to the researchers. Our results show that children indeed preferred buttons augmented with paper circuitry, demonstrating more attention for and increased believability in the function of these buttons as well as the overall system. These findings show how designers can use paper circuitry to more effectively engage children while play-testing their paper prototypes.

CCS Concepts

•**Human-centered computing** → **Interface design prototyping;**

Author Keywords

Children; prototyping; paper prototyping; mixed fidelity; design tools; paper electronics; paper circuitry

*These authors contributed equally to this work.

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INTRODUCTION

Paper prototypes are commonly used during the iterative design process to quickly and affordably test interface concepts. Since paper prototyping occurs over multiple stages of development, the user must agree to pretend that certain static elements, such as buttons, are functional even when they are not. However, using paper prototypes to test the design of interactive interfaces with young children can be difficult because it is harder for them as digital natives—persons who are brought up in the age of technology—to accept the shortcomings of a low-fidelity and static prototype [16]. We believe that using new technologies, such as circuit stickers [22], can have the potential to add interactivity to presently static prototypes without losing the design affordances of paper.

Purpose

In this paper, we will explore how incorporating paper circuitry into static paper prototypes has the potential to add additional levels of interactivity when play-testing with children. Through our study, we aimed to discover what affordances electronically augmented paper prototypes have over paper-only prototypes with respect to (*i*) keeping children's attention, and (*ii*) inspiring children's believability in the technical functionality of the prototype.

RELATED WORK

Paper prototyping is a technique widely used in the field of user-centered design to rapidly test interface concepts [32, 26, 24]. It involves both the creation of low-fidelity interfaces that represent a software system and the use of these interfaces to observe how a potential end-user would use and navigate through them [32].

Paper prototyping has a number of benefits. It allows designers to get user feedback early on in the design process, experiment with different interface designs in a low-cost environment, and involve team members with limited software skills in the interface development [32, 24]. The low-fidelity nature of the interface helps users feel more comfortable critiquing and suggesting major changes to the interface during the testing session, instead of focusing on the stylistic finish of a polished interface [24].

Traditionally, paper prototypes consist primarily of pieces of paper with marker-drawn interfaces, along with other materials such as cardboard, sticky notes, binder clips, etc. [24]. Sometimes, designers also integrate digital materials such as smartphones into traditional paper prototypes to enhance the experience. For example, a phone can be used to play music when a user presses the play button on the paper interface [4].

Typically, there are at least three roles in a paper prototyping test: facilitator, computer, and observer [32]. The facilitator is responsible for presenting the user with instructions and scenarios where they would use the interface and encouraging them to vocalize their thoughts during the testing process [24]. The person playing the computer role—the "technical assistant"—is responsible for manipulating the interface and, in some cases, providing scripted voice feedback that is meant to come from the interface itself. They are not allowed to explain how the interface is intended to work. The observer(s) are responsible for taking notes throughout the user-test [24].

Testing a paper prototype with a user is one type of Wizard of Oz (WOz) evaluation [32]. In a WOz evaluation, "some or all of the interactivity that would normally be controlled by computer technology is imitated, or 'wizarded,' by a human" [16]. For this test to be effective, the user must pretend that the paper interface is working even if presented with contrary evidence by the person playing the WOz [16].

New Mediums for Augmenting Paper Prototyping

With advancements in circuitry design and prototyping methods, designers can now integrate functioning circuitry into their paper prototypes, called paper electronics or paper circuitry. This adds interactivity to their palette while keeping the material and expressive affordances of the paper medium. Examples include using copper tapes [21], conductive paints [3, 29], and conductive inks [12] to fabricate flat and flexible circuitry onto paper. Such circuitry can also be folded and assembled to construct three-dimensional pop-up and mechanical elements like pull-tab switches and volvelle potentiometers, taking advantage of the structural properties of paper [21].

Such paper circuitry techniques are particularly suitable for paper prototyping because the tools and materials are commercially available off-the-shelf, the techniques are friendly to use for novices [5], and the process itself is quick and affordable enough to allow for many iterations. As a result, researchers within the HCI community are beginning to explore the possibilities and implications of such techniques for paper prototyping [17].

Paper Prototyping with Children Specifically

In this paper, we evaluate paper prototyping with children. In doing so, it is important to recognize that children have different relationships with technology than adults and that the evaluation process is likewise different. For example, unlike adults, children may simply walk away from a device if they find it uninteresting. Thus, it is important to build interfaces that keep the children's attention. Children may also have higher expectations of technological devices, under the belief that "technology is magic," so they may be disappointed if there is a mismatch in what the device can actually do [16]. Factors like these are important in designing not only the final product, but also the prototypes in order to get an accurate understanding of how a user will engage with the interface.

Within the HCI community, there are some preliminary studies on paper prototyping specifically for children. Sim et. al. [30] found that in the context of mobile games, there was little difference in usability and experience between low-fidelity paper prototypes and high-fidelity prototypes on a tablet device. Furthermore, a subsequent study shows that given identical graphics on an iPad tablet versus a paper prototype, children actually rated the graphics on the paper prototype higher. One possible explanation is that since the iPad is a higher fidelity technology, children may have had higher expectations for prototypes on this device [31]. Following this direction of inquiry, we investigate how adding a medium-fidelity technology, such as paper circuitry, influences children's reactions to a prototype.

Storytelling and Pretend Play to Assess Mental Models

To understand if using paper circuits will create more engaging and believable prototypes to play-test with children, it is important to understand how children perceive technology, and what methods exist for assessing the believability of technology. Unfortunately, the research on children's perceptions of technology is somewhat limited.

One vein of research examines how children as digital natives perceive technology differently than adults who did not grow up with technology. Research by Bryant [2] asked 201 children under age 12 to draw pictures of how they see interacting with technology in the future. Through analysis of the drawings, they found that children did not perceive a barrier between the physical and digital worlds, but instead saw technological devices as being able to serve as an extension of themselves, especially during immersive experiences such as simulated travel. Though this research suggests that children are more likely to expect the immersion of technology into their physical world, it also suggests that children expect technology to be seamlessly integrated, and they may not be as lenient when inevitable "bugs" or technological difficulties occur [10]. Therefore, it is natural that play could be one way in which to assess children's perceptions of technology.

Another vein of research on children's perceptions of technology surrounds the process of children as designers. In this way, children get to think critically and design a product for a target user, thereby exercising their creativity and problem-solving skills while also demonstrating their beliefs about technology. Most research in this area focuses on children over age 10, but few focus on early childhood perceptions of technology [34, 11]. Work by Benson and Lunt [1] mentions the importance of using real life contexts, which for young children may be rooted in fantasy and storytelling, to engage children in the iterative design process. In other words, research consistently highlights that pretend play and storytelling are two great ways of structuring the environment to assess children's beliefs and preferences about technology [1, 18].

Active participation in play is an important practice that supports children's social and cognitive development [27, 19, 20, 33]. Researchers argue that both storytelling and enactment in imaginative play are encompassed in the field of narrative activity because they mutually support the child's experience and development [8, 19].

Storytelling and imaginative play give adults an insight into the developing mental models of young children who may not be able to verbally express their preferences and opinions [16]. For example, research has consistently supported that children's problem-solving and reasoning skills are enhanced when they are engaged in pretend play and fantasy-driven stories [15, 6, 7, 9, 14, 25]. Although none of these research studies specifically examined children's reasoning skills in relation to how they perceive technology, these methods are still valuable in measuring the underlying mental models of how children perceive the world and their ability to develop and exercise abstract thought through pretend play [15, 35]. Therefore, in light of this research, we used storytelling and pretend play methods to assess the extent to which the inclusion of paper circuitry during design and prototyping will make the physical prototype more believable and engaging for young children.

From this literature review, we can conclude that paper prototyping is an important part of the design process, especially when designing for children. However, there is little research on paper prototyping with children and using storytelling and pretend play methods to assess the mental models of how children's perceptions of technology influence their experiences when play-testing. In this paper, we aim to address this gap by designing a study that uses a outer space-themed narrative to evaluate children's perceptions of technology by incorporating paper circuitry into paper prototypes.

METHODOLOGY

Participants and Study Design

To investigate our research questions, we conducted a two-day study in a science museum with 20 children (7 female and 13 male) between the ages of 3 and 10 years-old (1 child, age 3; 3 children, age 4; 1 child, age 5; 3 children, age 6; 4 children, age 7; 4 children, age 8; 2 children, age 9; 2 children, age 10). Depending on the preference of the family, children were accompanied by an adult guardian or participated by themselves.

Each child participated in one 20-minute session. At the start of the session, the child met two researchers—the facilitator and the technical assistant. The facilitator introduced the child to the activity as an interactive storytelling session about a journey to Mars in which the child will interact with a paper prototype version of a voice-controlled rocket ship.

The study was divided into three phases: (Phase A) take-off, (Phase B) on Mars, and (Phase C) back to Earth, which correspond to three interactive interfaces on the paper-prototype (Figure 1). Each interface had two sets of paper buttons: one set that lights up when pressed (Figure 2) and another set that does not. We also created a script that structured the "mission to Mars" narrative with three sections corresponding to the

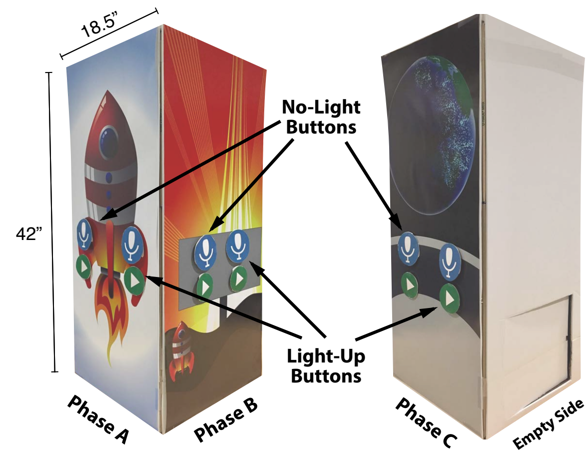

Figure 1. The paper-prototype used in the study. The prototype had three interfaces, one for each phase (Phase A, B, and C), created on the sides of a large box. Each interface contained one set of light-up buttons and one set of no-light buttons for children to choose from, and a background image that provided a visual for the phase setting.

three phases of the study (Phase A, B, C), and one section at the end of the script that served as the feedback questionnaire (Figure 3). Using the script, the facilitator directed the child three times to record a sound by pressing the paper-prototyped record buttons. For the first two recordings, in randomized order, the facilitator (*i*) designated which set of buttons (light-up or no-light) to use so that the child could try out both types of buttons and (*ii*) asked the child to playback their recording using the corresponding playback button (QA-1, QA-2, QB-1, QB-2, QC-1, QC-2, Figure 3). In the third recording, the child chose which button he or she preferred to use (light-up or no-light) (QA-3, QB-3, QC-3, Figure 3).

In Phase A, there was no actual recording so playback did not work for both the light and no-light conditions. In Phase B, the technical assistant used a smartphone in plain view of the child to mimic the record and playback functionalities of both sets of buttons. In Phase C, one set of buttons had no light but was connected to a computer (out of view of the child) so that the buttons actually recorded and played back. The other button set in Phase C had lights, but did not record. Instead, the technical assistant recorded and played back the message on a phone in view of the child.

Between each phase, the facilitator posed a transitional question to the child (TQ-A, TQ-B, and TQ-C, Figure 3). This question used multiple phrasings to ask: "Which button do you think works better and why?" At the end of the mission, the facilitator asked three questions about the child's perceptions and preferences (EM-1, EM-2, and EM-3, Figure 3), all while under the pretense of documenting the technical difficulties the astronaut experienced so that they could make sure to fix the problems for the next mission.

Since the literature emphasizes the importance of using immersive storytelling and play to assess the mental models of children, we designed our study to tell a cohesive, immersive story during the entire study session. Rather than creating

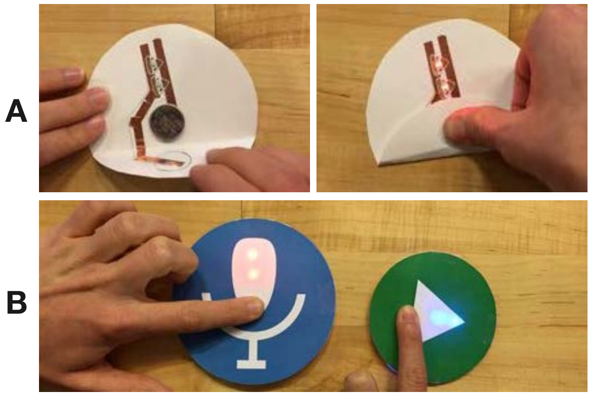

Figure 2. Light-up paper prototype buttons. (A) Circuitry inside the light-up paper buttons (B) and the light-up buttons when pressed such that the lights turn on.

a control group, we designed the first phase of the mission (Phase A) to serve as the control, where children could interact with both a nonfunctioning no-light paper button, and a nonfunctioning light-up paper button. These buttons were displayed side-by-side, in order to allow children to demonstrate their perceptions of the technology by comparing the buttons and making decisions through play that naturally aligned with the immersive narrative.

Button Design

We created two types of buttons: a large "record" button with a microphone icon and a smaller "playback" button with an arrow icon. Every button was made up of two cardstock circles with one circle folded at one edge to create a springy hinge, taped together to form a clam-like structure. For the buttons with circuitry, we used copper tape, coin batteries, and circuit sticker LEDs [22] (Figure 2A) to make a circuit inside the clam structure such that, when the button was pressed, two LEDs turned on and illuminated the button (Figure 2B). Because the circuitry was hidden within the button, there was no visible or tactile difference between buttons with circuitry and buttons without when the LEDs were off.

There was only one set of working buttons in the experiment. To create these buttons, we used a laptop with custom software to (i) record audio, and (ii) play back the most recent audio recorded. We plugged a Makey-Makey circuit board into the computer to connect the paper buttons [23]. Again, there was no visible or tactile difference between the working buttons and the buttons with and without circuitry.

RESULTS

Both quantitative and qualitative results were collected during the study. In each phase, we noted which record button the child chose to use for the third question in each phase (QA-3, QB-3, QC-3). For each transition question (TQ-A, TQ-B, TQ-C), we noted which button they believed worked better, and their explanation of why they believed this button worked better.

To compute the statistical significance of our observations, we used a Binomial test: It tests whether the observed proportions

Phase A: *Rocket is making a funny sound. Researcher prompts child to record the sound the rocket is making.*

QA-1: Tap on this record button to record the sound the rocket is making. Then press play to make sure that your recording is correct so we can send it through to mission control.

QA-2: Now try this other record button and make the noise again. Remember to play back your recording.

QA-3: Now we are ready to take off! This is a voice-controlled rocket, so you need to record your voice and tell the spaceship to blast off! You can press either button to record it!

TQ-A: Which button do you think will be easier to fix and why?

Phase B: *Researcher congratulates child on a safe landing on Mars! Prompts child to record a message for his/her family and a message for his/her friends.*

QB-1: Use this button to record your message to your family to let them know you got to Mars safely! Remember to make sure you listen to your message after you record it to make sure it is correct before it sends.

QB-2: Use this button to record your message to your friends to let them know you got to Mars safely! Remember to make sure you listen to your message after you record it to make sure it is correct before it sends.

QB-3: Lastly, you need to send a message to NASA and tell them about Mars, what do you see? NASA intercepts all messages to ground, so you can use either button to record your message to NASA.

TQ-B: Why did you choose that button to send your message to NASA?

Phase C: *Researcher explains to child that they are now about to re-enter Earth's atmosphere. In order to do so safely, the child must complete three steps.*

QC-1: First, you have to use this button to tell the rocket to deploy the shields. Don't forget to play your recording back to make sure your commands are correct!

QC-2: Next, you need to use this recording button to tell the rocket to open the parachute. Make sure you listen to your recording!

QC-3: Lastly, you can use either of these buttons to tell the rocket it is time to go! Just clearly say, "Blast Off"!

TQ-C: Which button do you believe works better to control the rocket and why?

End of Mission Questions: *Researcher congratulates child on a successful return to Earth and asks child if she can ask some follow-up questions.*

EM-1: Which buttons do you think worked best and why?

EM-2: Which buttons did you like best and why?

EM-3: If we did this again, which buttons would you want to use?

Figure 3. The scripted questions that the facilitator asked during and between phases of the study.

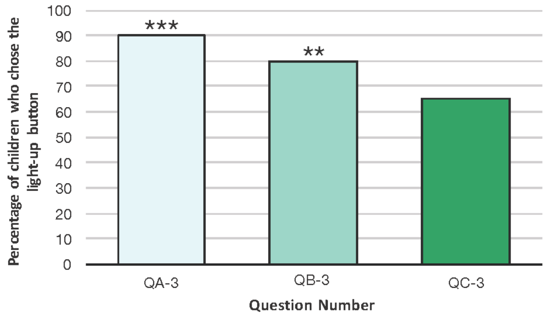

Figure 4. Percentage of children who chose to use the light-up button. In QA-3 and QB-3, we find a statistically significant difference (*p < 0.05, **p < 0.01, ***p < 0.001).

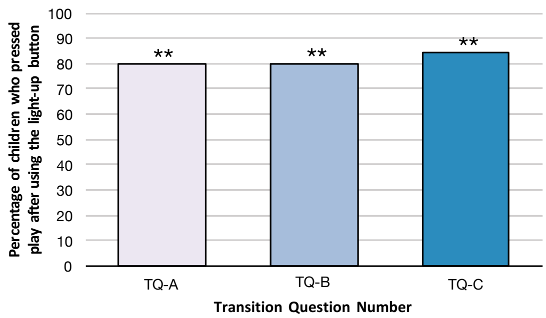

Figure 5. Percentage of children whose chose the light-up button in their transition question answers. In TQ-A, TQ-B, and TQ-C, we find a statistically significant difference (*p < 0.05, **p < 0.01, ***p < 0.001).

(e.g. the fraction of participants that pressed a certain button out of all participants) are significantly greater than 50%. High statistical significance (i.e. low p-value) indicates that the observed results are not just due to random chance [13].

We used children's explanations for all transitional questions (TQ-A, TQ-B, TQ-C) and the three end-of-mission feedback questions (EM-1, EM-2, EM-3) to code for whether their responses were purposefully related to the button or not. For example, if a child explained that they selected a button because "the button lights up" or "because the button is blue and blue is my favorite color," these would be coded as YES, as their reasoning was related to the button's properties. However, if they provided explanations such as "because I want to" or "I don't know," these would be coded as NO, as their reasoning was not related to the button's properties. We then ran our results to reflect (i) an aggregate of children's answers irrespective of the validity of their reasoning and (ii) only children's answers that related to the button's properties.

Phases: Which Button Did the Child Choose to Use?

We analyzed which button children selected at the end of each phase when given a choice (QA-3, QB-3, QC-3). We found that children tended to choose the light-up buttons in each phase: 90% of the time for QA-3, 80% of the time for QB-3, and 65% of the time for QC-3. These findings were statistically significant for QA-3 ($p = 0.0002$) and QB-3 ($p = 0.0059$), meaning that children's tendency to choose the light-up button did not occur due to random chance (Figure 4).

Phases: Which Button Did the Child Think Worked Best?

After each phase, the children were asked a transitional question (TQ-A, TQ-B, TQ-C) to determine which button they thought worked better. We analyzed their responses and found that 80% of the children answered the light-up button for TQ-A ($p = 0.0059$) and TQ-B ($p = 0.0059$), and 84% for TQ-C ($p = 0.0022$) (Figure 5). Using the coding process discussed at the beginning of this section, we then filtered the results to look at only the children whose answers related to the button's properties. We still found a statistically significant difference between those who chose the light-up and no-light buttons (TQ-A, $p = 0.0287$; TQ-B, $p = 0.0017$; TQ-C, $p = 0.0065$). Thus for each phase, children were more likely to believe that the light-up button (with the paper circuitry) worked better than the no-light button (without paper circuitry) even when their answers were filtered for relevance. This preference for the light-up button was statistically significant across all phases both for filtered and non-filtered answers.

End of Mission: Which Buttons Did the Child Think Worked Best?

At the end of the mission, children were asked to answer feedback questions (EM-1, EM-2, EM-3), with EM-2 asking which buttons they felt worked best overall. Since the final feedback questions pertained to all of the buttons used during the course of the entire mission, children were able to select multiple buttons for one answer. Thus, we used a non-parametric statistical test [28] to test whether the observed choices are not simply due to random chance. We ran 100,000 simulations to get a null distribution. Then to compute a p-value, we calculated how often the simulation results were the same as or more extreme than the actual observed results (*p < 0.05, **p < 0.01, ***p < 0.001).

We found that 85% of children chose at least one light-up button in their response to EM-2. We found that 65% of children exclusively selected light-up buttons for EM-2 ($p = 0.0007$), and when we filtered the results to look at only responses that related to the button's properties, 77% chose only light-up buttons for EM-2 ($p = 0.0003$). Thus, the percent of responses that contained exclusively light-up buttons increased when the answers were filtered for relevance to the buttons. Regardless of the small sample size ($n = 20$), these findings are statistically significant, meaning that children consistently expected the light-up buttons to work better in their responses to the end-of-mission questions, and this was not due to random chance.

DISCUSSION

Our results show that children indeed preferred buttons augmented with paper circuitry, demonstrating more attention for and increased believability in the function of these buttons as well as the overall system. When children were given the chance to press either a light-up or no-light button, a majority chose to press the light-up button. When asked which button they felt worked best after each study phase, a statistically significant majority chose the light-up button after all three phases. When asked why they chose the light-up button(s) in their answers, many children's responses included direct references to the buttons' light-up properties.

We found that many children linked the functionality of lights to mean greater functionality of the buttons' ability to record and play sound, indicating increased believability in actual technological functionality. Many children explained that the light represented better functionality throughout the phases. For example, one child explained that she thought the light-up button worked better "because I see the red light and that means that it's working." Another child chose to use the light-up button "because it lights up and the computer can get a better sense." When asked why he thought the no-light button would be more difficult to fix, one child responded "because on the left we would have to fix the light too," implying that he believed in a connection between the functionality of the simple light and the more advanced record, playback, and communication functionalities.

Even in Phase C, where one set of buttons actually recorded and played back, but did not light up, a majority of children preferred the light-up button where the recording was visibly activated by the technical assistant. When told after the study that the light-up button in Phase C did not actually record or playback, one child even asked "then why did the red light glow?" Again, the child implied a connection between lighting up and recording, indicating a higher believability in the technological functionality of the prototype when a simple light was present.

Many children would not begin speaking for the recording until the buttons were steadily illuminated. When the button flickered (which occurred if not pressed hard enough), these children would often shift their pressure on the button until the light shined steadily and then begin speaking. We even observed some participants repeat their recording if the light went off in the middle of their previous attempt. In this scenario, the children may have expected that the recording function was working when the light was on, and thus would change their behavior to make sure they recorded their voices properly using the light-up button.

Our study shows that incorporating paper circuits indeed enhances children's interactions with paper prototypes. Simply putting LEDs on buttons provides feedback to the child that the system is responding to their behavior in a way that static paper-only prototypes do not, increasing the child's interest in and attention to the system. Light as indication is also a powerful tool for designers because it is abstract enough to indicate any number of technological functions. In our case, the light successfully linked the buttons to recording and playback behaviors for the child, even though in actuality these functionalities were independent of the button.

While we find paper circuitry to be a powerful tool for augmenting traditional paper prototyping techniques, our results also show that such interactivity must be carefully designed to align with the narrative and the purpose of the prototype. Otherwise, as in the case of Phase C, light-up feature may compete with the intended functionality of the prototype. That is, in designing paper prototypes to include electronic interactivity, it is important to design electronic feedback so that the interactivity itself does not draw participants' attention away from the core purpose of the prototype.

Limitations and Future Work

There are limitations within our study, which we aim to address in future research around paper prototyping with children.

First, by choosing a button with a clear function, such as a recording button, our goal was to try and understand whether children would believe that the button was more likely to work when it lights up. However, the definition of "working" is still relatively ambiguous, and was not defined in this nor, to the authors' knowledge, in other studies on children's perceptions of technology. Children's evaluation of the functionality of the prototype may be largely influenced by their perceptions of "working" features, rather than the button's intended function. For example, two children commented that the light-up button worked better because buttons are meant to light up. According to these children, the functionality of the button is not necessarily to record, but to give feedback for pressing, such as light.

Another limitation was the age range of the children, which spanned from ages 3 to 10 years old. Children at these different ages may have different expectations of technology. Older children have had more exposure to and developed more expectations of what technology is supposed to do. In our future work, we plan to look at how children's perceptions of the buttons differ across age brackets.

Lastly, although our prototype was not intended to replicate a UI that we aim to use in a mobile, web, or tablet application, many low-fidelity, paper prototypes are often larger in size than the final product. We are curious whether the size of the prototype, especially if it is disproportionate to the final interface design, is important to consider when designing low-fidelity prototypes for children. We plan to incorporate this question of size into our future work.

CONCLUSION

We conducted a study where children used a voice-controlled rocket to go on a mission to Mars, and used different paper recording buttons to examine whether using paper circuitry to have some of the buttons light up would extend the believability of the button's functionality. We found that children consistently believed that the buttons that lit up worked better than the non-light-up buttons. These results have implications for designers to incorporate new technologies, such as paper circuits, into their low-fidelity prototypes in order to engage children and increase interactivity during play-testing.

SELECTION AND PARTICIPATION OF CHILDREN

Twenty children, ages 3 to 10 years old, participated in this study. All participants were visitors to a science museum in the Greater Boston Area. Families visiting the museum were asked if their children would like to participate in a research study involving an "interactive storytelling session about a journey to Mars." Once families showed interest, guardians were informed about the study's purpose and asked to sign the written consent form. Children (and sometimes their guardian) then entered the study room. Before beginning the study, a researcher asked the child for verbal assent. All procedures were approved by our Institutional Review Board.

Once the study was completed, researchers showed children how the light-up buttons worked and answered questions about the system and the study.

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