# Debugging as Authentic Inquiry in Early Childhood: A comparative case study using the CRISPEE prototype

**Abstract:** This research explores ways that children engage in inquiry practices while using CRISPEE, a novel tangible technology to explore bioengineering. This paper presents two case studies of 6-year-old children's inquiry with CRISPEE. These cases were selected because of prototype malfunctions that occurred, allowing us to explore children's inquiry when faced with inconsistent feedback from CRISPEE. Results were situated within Chinn & Malhotra's (2002) inquiry framework. The data suggest that debugging may be a useful frame to engage young children in authentic science inquiry.

## Introduction

The goal of this exploratory study was to investigate ways that children engage in inquiry with a prototyped tangible technology. Education researchers argue that inquiry, or "[how] scientists study the natural world and propose explanations" (National Research Council, 1996, p. 23), is critical for children's 21st century participation (Anderson, 2002; AAAS, 1993; Gallenstein, 2005; Mantzicopoulos, Patrick, & Samarapungavan, 2008; Marshall & Horton, 2009; Quigley, Marshall, & Deaton, 2011). However, learners show difficulty attending to evidence inconsistent with their current theory (e.g. Dunbar 1993, Hammer, 1994).

Debugging, another 21st century skill from the field of computer science, can support inquiry practices in elementary-aged students (National Research Council, 2012; Sullivan, 2008). Debugging relies on attending to errors and discrepant evidence in order to gain fuller understanding of the technological system in which the "bug" occurred (Bers, 2018; Papert, 1980).

The present article describes findings from a user interaction study involving CRISPEE, a novel tangible technology designed to introduce foundational concepts of bioengineering. We present a case study of two 6-year-old children from a larger user-study the CRISPEE prototype (all names presented are pseudonyms). A surprising finding was that children who observed malfunctions or "bugs" in early versions of the prototype were still able to correctly learn how to use the tool.

**Theoretical Framework**

Engagement in authentic science inquiry is critical for learners to become active participants in 21st century civic economies (Kolstø, 2001; Roth & Désautels, 2004; Sandoval, 2005; Sperling & Bencze, 2010). Prior research suggests that preschoolers do not hold consistent notions about the purpose or process of experimentation (Dean & Kuhn, 2007; Klahr & Nigam, 2004; Schauble, 1996). However, children as young as five can alter their beliefs in light of counterevidence, suggesting that children's barriers to inquiry may be rooted in a lack of experience and not a developmental gap (Macris & Sobel, 2017; Bauer & Booth, 2019; Sandoval & Morrison, 2003; Sodian, Zaitchik, & Carey, 1991; Tschirgi, 1980; Schauble et al., 1995).

Chinn and Malhotra (2002) proposed a theoretical framework for evaluating school-based science inquiry tasks. Their framework defines how practices of science inquiry can occur authentically, in contrast to how these practices are packaged into simple inquiry tasks often taught in schools (Chinn & Malhotra, 2002). For example, authentic inquiry involves scientists generating their own research questions, while in simple inquiry tasks, questions are predetermined for students (Chinn & Maholtra, 2002, p. 181).

In a recent study of 363 5-to-9-year-olds, Busch & Legare (2019) found that inconsistent and ambiguous evidence, rather than consistent evidence, was more likely to motivate children to actively seek information to explain their observations. In one study of a middle school science and technology intervention, researchers attributed students' significantly increased inquiry reasoning to their robotic debugging experiences (Sullivan, 2008).

In the current study, we extend this research by exploring young children's engagement with inquiry as they seek to understand discrepant feedback with a novel technology (Sandoval, 2005; Kelly, Chen, & Crawford, 1998; Kelly & Duschl, 2002). Specifically, we compare two cases: one of a child who engaged in simple inquiry with a novel technology, and another who engaged in authentic inquiry with the same tool (Chinn & Malhotra's 2002).

**The CRISPEE Technology**

The tangible CRISPEE tool allows children to model how changing a simple gene sequence or "program" can result in altered features of an animal's body, specifically, the color of a bioluminescent animal's light. Children can choose a naturally-occurring bioluminescent animals (e.g., firefly) and code it to glow in their programmed color (Strawhacker et al., 2020; Verish at al., 2018).

The prototype comprises six "gene" blocks representing the primary colors of light (red, green, and blue) that can be turned On (taller solid-color blocks), or Off (shorter X-marked blocks). Children can combine three blocks (one of each color) and test their program in a multi-step process, resulting in an output color (see figure 1). The ouput color is displayed on the CRISPEE using an oversized LED bulb inlaid in an illustration of an animal.

<insert figure 1>

**Method**

The goal of this research was to investigate ways that children engage in science inquiry while using the CRISPEE tool. Specifically, our exploratory research question was, "how does debugging with the CRISPEE prototype support engagement with the practice of science inquiry?” The study method is rooted in Sandoval’s (2005) recommendation that researchers look at learner’s actions and expressed beliefs to learn about how they make sense of science questions. A comparative case study was used to understand the mechanisms of inquiry in which children were implicitly or explicitly engaged (Merriam, 2009; Yin, 2014; Stake, 1995; Zainal, 2007).

The two cases described here were collected as part of a larger study of child user interactions with the novel CRISPEE prototype. Children in the study participated in a 15-20 minute semi-structured session with CRISPEE, and worked (alone or in pairs) with a researcher while they explored CRISPEE. Video footage of all sessions was collected at museums, schools, and informal camps in the Greater Boston area from $N$ = 108 children (aged 4-9 years, average age 6 years), and contributed to the development of a coding scheme about children’s inquiry with CRISPEE.

Both cases were selected because they encountered a bug in CRISPEE’s feedback lights (flashing red/green lights on the interface) during step one of the interaction, which interrupted tests and required troubleshooting each time. During the first case, 6-year-old Zane, CRISPEE malfunction three times (37% of tests), but mainly functioned correctly during 63% of his tests. The second case child, 6-year-old Yanni., experienced many more prototype malfunctions (79% of tests), allowing us to explore his inquiry when faced with inconsistent feedback from CRISPEE.

Detailed transcripts were generated of Zane’s and Yanni’s physical actions and spoken conversation to conduct an interaction analysis (Jordan and Henderson, 1995). A team of researchers conducted depth interaction analysis to map Zane’s and Yanni’s ideas while exploring CRISPEE.

**Results**

All children explored how the novel technology worked, and how to code desired colors. Four main "ideas" about how to program a light using CRISPEE emerged in data from the larger study sample (see table 1). Children sometimes held multiple ideas at once. Zane's and Yanni's behaviors during each test were mapped these ideas.

<insert table 1>

***Narrative Case Example: Zane***

Zane focused on using all six blocks in his program creations (see figure 2), indicating that he believed something besides the three block slots was related to the resulting light color (see table 1).

<insert figure 2>

He tested a total of eight programs, and three showed the bug (see figure 3). During all of his tests, Zane used six blocks by stacking three blocks into the platform slots and fitting the rest around or on top of the others. His structures became progressively more sturdy, and near the end of his session, he voiced a goal to build his blocks "like stair steps". Zane also took note of the sequence of blocks in the platform slots, and the feedback lights.

<insert figure 3>

During three of his tests, Zane witnessed a feedback light bug. The first time, he stepped aside to let the researcher quickly troubleshoot and repair CRISPEE. The second time, he seemed to notice the bug, and began to reason about the feedback lights, saying, “Hmm, maybe these two are green because the light [under button 1] is flashing green…?” but the researcher had already repaired CRISPEE before he completed his thought. The third time he witnessed a bug, Zane intently watched as the researcher debugged for over 45 seconds, but offered insight into what he was thinking.

***Narrative Case Example: Yanni***

<insert figure 4>

At the start of his play-session, Yanni stated that the sequence of the blocks would control the light color (see table 1), and justified this hypothesis by referring to another programming language he was familiar with (see figure 4). Yanni and his partner built and tested 28 programs with the CRISPEE kit (see figure 5).

<insert figure 5>

Yanni’s CRISPEE was severely buggy, which resulted in frequent contradictory feedback in response to his explorations. Yanni began by testing multiple permutations of the same two programs (all “On” blocks, and all “Off” blocks), saying that the solid and X-marked blocks could not be mixed. During test 7, he accidentally removed a block from CRISPEE in the middle of a test, which turned on the “buggy” feedback light. After this, he deliberately tested non-functional programs with missing blocks at different points, as if he was confirming the one consistent rule to the feedback lights. Eventually, he rejected his sequencing idea to explore how the feedback lights worked. During his final test, Yanni planned and built a yellow light, which he triumphantly showed off. He explained that he knew how to make it because there were no red feedback lights.

***Cross-Case Comparison: Simple and Authentic Inquiry Practices with CRISPEE***

Zane and Yanni exhibited two unique ideas about how the CRISPEE technology worked, but initially their approach was the same. Both children took up the research task presented, a simple experimental task according to Chinn & Maholtra's (2002) definition. Similarly, both children formulated their own authentic research questions.

Zane identified block towers, block sequence, and feedback lights as potential causes for changing CRISPEE's light. However, he encountered an authentic inquiry challenge of not knowing how to isolate these variables. As a result, he seemed to hold more than one idea at once about how to change the CRISPEE light, and was either unable or uninterested in disentangling which variable was most salient. He concluded the session with the same incorrect explanatory ideas as when he began.

Like Zane, Yanni was interested in block sequence and feedback lights as mechanisms for controlling light color. However, his unexpected discovery that leaving a block slot empty would *always* result in a red feedback light offered him insight into a new area of authentic inquiry: identifying a control variable. Yanni engaged in several authentic inquiry practices to form his correct idea about CRISPEE functions, including selecting variables, coordinating multiple results, and relating data to his research question (Chinn & Malhotra, 2002).

**Significance**

Our exploratory research question was, "how does debugging with the CRISPEE prototype support engagement with the practice of science inquiry?" This case study recalls Busch & Legare's (2019) recent finding that inconsistent and ambiguous evidence (such as a bug) evokes stronger attempts from learners to seek information and solve problems. The current study has implications for educational technologies, which naturally exhibit inconsistent feedback in the form of malfunctions over time. We propose that children may be able to learn about technologies through their failures and bugs, perhaps even better than if the technology were functioning correctly. Educators and researchers can take two practice recommendations from this case study. First, when children seem to be consistently "failing" at using a functional technology, we can recall that they may be attempting to engage in authentic inquiry about the interaction rather than failing to understand how it works. Second, malfunctioning technology offers children an opportunity for authentic inquiry. Children can be co-investigators with adults, who can model troubleshooting and problem solving practices. In conclusion, these exploratory results suggest that playing with buggy tech can be just as engaging and cognitively stimulating as working with perfectly functional technology. We propose that just as we seek authentic science inquiry experiences for children, so should we seek authentic debugging experiences to support their developing inquiry practices.

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Verish, C., Strawhacker, A. Bers, M. U., & Shaer, O. (2018, March 18-21). *CRISPEE: A Tangible Gene Editing Platform for Early Childhood*: *Proceedings of the Twelfth International Conference on Tangible, Embedded and Embodied Interaction (TEI)*, Stockholm, Sweden. New York, NY: ACM.

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**Tables**

Table 1

Ideas that children expressed about how to change CRISPEE's light color.

| Idea Type | Explicit Evidence | Implicit Evidence |
|---|---|---|
| A) **Sequence** of blocks activates colors | - Predicts that order/sequence of the blocks will impact light | - Tests programs with same blocks in different order multiple times<br>- Attempts to debug a correct "off" program, expecting to see light |
| B) **X blocks adds** color | - Predicts that X blocks affect light by adding or increasing light<br>- Predicts that mixing On and Off of same color will make "more" of that color<br>- predicts that X blocks will affect hue (lightness/darkness) of light | - Leaves empty slot (rather than adding X)<br>- Attempts to debug a correct "off" program, expecting to see light<br>- Tests programs with both On and Off blocks of same color |
| C) **X blocks inhibit** color | - Predicts that X blocks affect light by removing or decreasing light<br>- Predicts that mixing On and Off of same color will not work (e.g." this will confuse CRISPEE") | - Debugs by removing On and Off blocks of same color<br>- Tests programs with one of each of the three colors<br>- Does not mix On and Off of same color in one program |
| D) **Something else** other than block color activates light | - Predicts that feedback lights relate to block color (e.g. red light means add a red block)<br>- Predicts that one location or slot activates light differently (e.g. "this slot is stronger")<br>- Predicts that On and Off blocks cannot be mixed (e.g. says they are "different languages") | - Tests alternative (e.g. upside-down, stacked) block configurations<br>- Tests other interactions besides blocks (e.g. buttons, animal faceplates) |

**Figures**

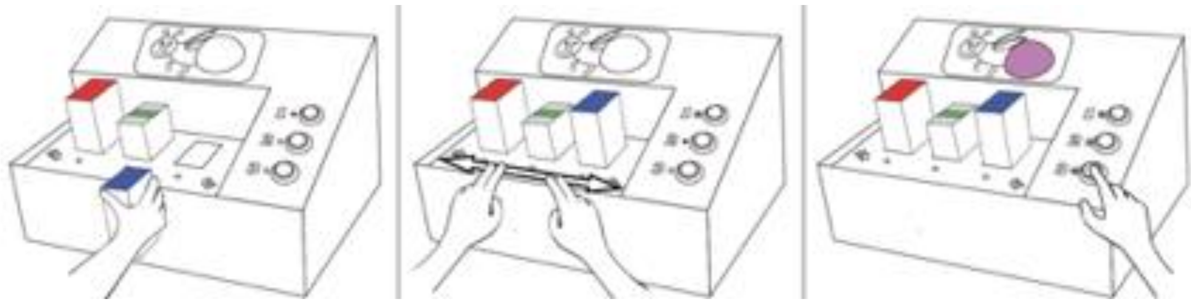


Figure 1. Three-step CRISPEE interaction (reprinted with permission from original author) (Verish et al., 2018).


Figure 2. Zane builds a CRISPEE program with all six blocks, attempting to build a sturdy tower that will withstand the shaking platform.

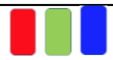
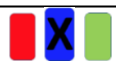
| Test | Program | Bug | Light Result | Stated Goal | Idea About What Caused Light Result | Reaction to Evidence |
|---|---|---|---|---|---|---|
| 1 |  + extra blocks | | White | "build a tower with tall ones on bottom and short ones on top" | D) Something else | Surprise |
| 2 |  + extra blocks | | White | See it again | D) Something else | |
| 3 |  + extra blocks | | White | Change the order of the bottom and balance the blocks | A) Sequence and D) Something else | Satisfaction |
| 4 |  + extra blocks | X | Off | Make new color | D) Something else | Confusion |
| 5 |  + extra blocks | | Yellow | Make Red | D) Something else | Satisfaction |
| 6 |  + extra blocks | X | | Make last program | D) Something else | Uncertainty |
| 7 |  + extra blocks | | Off | Make blocks into a stairstep | A) Sequence and D) Something else | Frustration |
| 8 |  + extra blocks | X | White | Make a color | A) Sequence and D) Something else | Satisfaction |

Figure 3. Testing log from Zane's play session

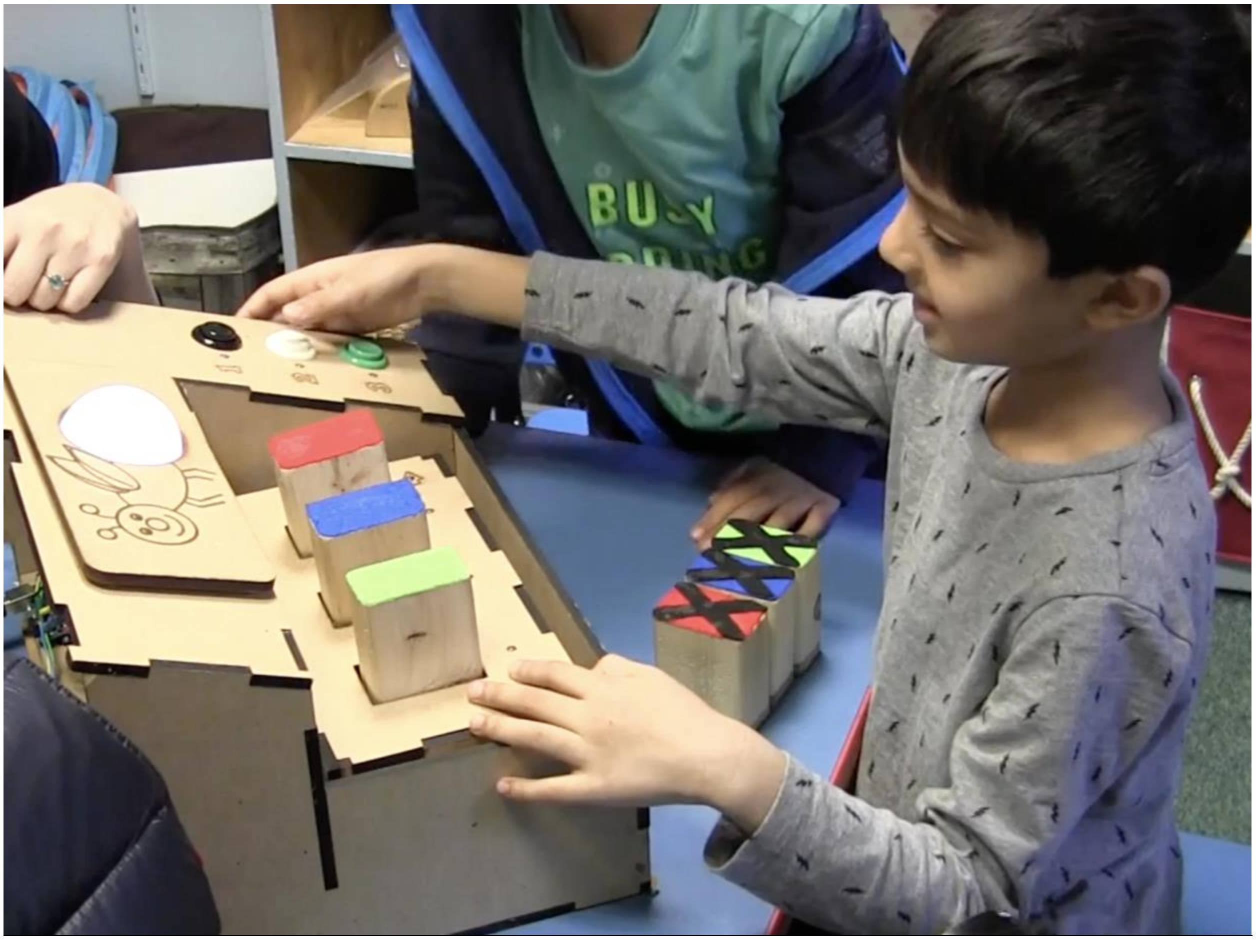
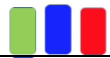
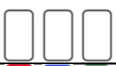
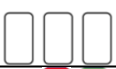
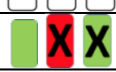
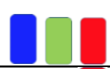
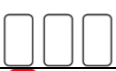
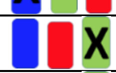
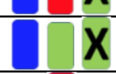
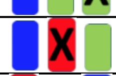
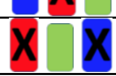


Figure 4. Yanni (foreground) tests a CRISPEE program Green On, Blue On, and Red On blocks, creating a firefly with a glowing White light. The Off (or X) blocks are arranged on the table in front of him.

| Test | Program | Bug | Light Result | Stated Goal | Idea About What Caused Light Result | Reaction to Evidence |
|---|---|---|---|---|---|---|
| 1 |  | | White | Try all “big blocks” | A) Sequence | |
| 2 |  | X | White | | A) Sequence | |
| 3 |  | X | White | | A) Sequence | |
| 4 |  | X | White | | A) Sequence | Satisfaction |
| 5 |  | X | Off | Try all “small" blocks” | A) Sequence | |
| 6 |  | X | | | A) Sequence | |
| 7 |  | X | N/F* | | A) Sequence | Surprise |
| 8 |  | X | Off | Make green feedback lights | A) Sequence | |
| 9 |  | X | | Make green feedback lights | A) Sequence | Frustration |
| 10 |  | X | N/F | Make red feedback lights | D) Something else | Excitement |
| 11 |  | | Off | Make new color | A) Sequence | |
| 12 |  | | Off | Make new color | A) Sequence | |
| 13 |  | X | Off | Make new color | A) Sequence | |
| 14 |  | X | | Make new color | A) Sequence | Frustration |
| 15 |  | X | N/F | Make red feedback lights | D) Something else | Satisfaction |
| 16 |  | X | N/F | Make Green | B) X adds color | Confusion |
| 17 |  | | White | Make green feedback lights | A) Sequence | Satisfaction |
| 18 |  | X | N/F | Make Red | B) X adds color | Frustration |
| 19 |  | X | N/F | Make red feedback lights | D) Something else | Satisfaction |
| 20 |  | X | N/F | Make Red | B) X adds color | Confusion |
| 21 |  | X | Yellow | Make green feedback lights | A) Sequence | Surprise |
| 22 |  | X | Purple | Make new color | B) X adds color | Excitement |
| 23 |  | X | N/F | Make new color | B) X adds color | Confusion |
| 24 |  | X | Cyan | Make Red | B) X adds color | Surprise |
| 25 |  | | Green | Make Blue | B) X adds color | Surprise |

| | | | | | | |
|---|---|---|---|---|---|---|
| 26 |  | X | N/F | Make Blue | B) X adds color | Confusion |
| 27 |  | | Cyan | Make new color | C) X inhibits color | Surprise |
| 28 |  | X | Yellow | Make Yellow | C) X inhibits color | Satisfaction |
| *Note: N/F = Non-Functional Program | | | | | | |

Figure 5. Testing log from Yanni's play session