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Designing with Genes in Early Childhood: An exploratory user study of the tangible CRISPEE technology

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A B S T R A C T

Biodesign, a speculative and creative offshoot from the field of bioengineering, is an area of STEM that is growing in popularity in education settings, primarily because of its unique interdisciplinary lens that connects STEM disciplinary knowledge and creative design practices. Although this trend is currently limited to middle school, high school, and higher education, prior research suggests that children 5 years and older, may yield long-term gains from exploring developmentally-appropriate concepts from novel STEM fields. Although there is little research on educational technologies or resources to support young children's curiosity and learning in this novel domain, some research suggests that young children may already be forming preconceptions about genetics and biology (e.g., from popular media). Tangible technologies, which provide children qualitatively new, developmentally appropriate ways to engage with ideas and techniques, have been shown to support children's engagement with foundational ideas relevant to biodesign, including the engineering design process. By applying developmentally appropriate constraints to our technology development (e.g., through frameworks such as the Positive Technological Development), the research team developed and evaluated a novel tangible technology called CRISPEE to introduce young children to concepts of biology and engineering. This article describes an experimental pilot study to investigate (1) how young children interact with the CRISPEE technological prototype, and (2) what prior knowledge the average child might bring to an educational biodesign activity. Implications for ongoing technology development and developmentally appropriate learning goals are discussed.

1. Introduction

Research suggests that young children may yield long-term gains from exploring developmentally-appropriate concepts from novel STEM fields, such as computer science and robotics [1–5]. In response to this finding, pedagogy that supports integrated STEM education and inquiry is becoming more pervasive in early childhood settings [6–9]. Most recently, educational initiatives for interdisciplinary and democratized STEM learning has led to a new domain entering the education stage: [4,10–13].

Bioengineering is the deliberate modification of an organism through the alteration of its genes, and among other applications, is used to create vaccines, and develop ecologically sustainable biofuels and plastics [14,15]. The related field of biodesign is a growing movement at the intersection of biology and design, that uses the creative design process to develop speculative solutions to human problems, such as "probiotic cosmetics, self-healing concrete, cow free-milk, or spider silk that can be woven into clothing" ([16–18], p. 33). Although it currently viewed as too advanced for early education, some research suggests that young children may already hold preconceptions about genetics and biology, gleaned from popular culture and media aimed at children and young adults [19–21]. Further, biodesign shares disciplinary practices and concepts with computer science, engineering, and biology, all of which have been successfully introduced in early childhood settings [1,9,22,23]. This suggests that biodesign may be an effective way to introduce young children to core concepts of biology and bioethics through the lens of engineering design and creative problem solving. Currently, there is little research on tools or resources to support young children's curiosity and learning in this novel domain, although research with older learners is steadily growing [4,13,24]. Additionally, tangible technologies have been shown to support children's engagement with foundational ideas relevant to biodesign, including instruction-based coding languages and the design process [1,25–27].

CRISPEE is a tool developed by the DevTech Research Group at Tufts University and the Human Computer Interaction Lab at Wellesley College, and was designed to engage young children ages 5–8 years in explorations of foundational biodesign. By iteratively designing CRISPEE to align with design frameworks for

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developmentally appropriate learning tools (e.g. Positive Technological Development; [28]), the authors sought to create a tangible tool for children to "touch and hold" tangible representations of genes, a necessarily abstract and microscopic topic that was previously unavailable to children through traditional curricular methods. The purpose of introducing these concepts in early childhood is not to prepare a bio-tech literate workforce, or unnecessarily increase the pace of the K-12 STEM curriculum, but rather to allow children a developmentally appropriate medium to explore topics at the intersection of science and society that they may already come into contact with in their daily lives, such as bioethics and cross-cutting scientific advances.

The purpose of this study was two-fold. First, we wanted to explore children's experience of the physical interaction of our tangible CRISPEE technology. This would inform the ongoing design research of the prototype, allowing us to leverage children's interactions to make the learning metaphors used in CRISPEE more relatable. Second, we wanted to explore what, if any, preconceptions children held about the topic of "genes" before any kind of CRISPEE intervention, in order to identify any popular preconceptions that young children might hold.

To explore these questions, we collaborated with the Boston Children's Museum to host a pop-up style exhibit featuring the CRISPEE technology. During each play session, children answered an open-ended question about genes to surface their relevant preconceptions. Then, children spent 10 to 20 min free-playing with the CRISPEE tool, working one-on-one or in groups of two with a researcher to document and prompt their explorations. While children played, parents and guardians were invited to complete a voluntary survey to gather information about the children's home and school experiences with science, engineering, technology, ethics, and design. Because only 44 families completed the survey (70% of the sample), aggregate responses will be shared here to contextualize the sample, but will not be reported on in results.

2. Related work

Most introductory biodesign education programs are targeted at older students in high school, college, or pre-professional training (e.g. [10,13]). However, prior research demonstrates that this type of program is already too late to change students' ingrained STEM attitudes, so they likely attract students who would already have been interested in STEM careers in college [29,30]. There are convincing practical and theoretical reasons to begin much earlier, including the lasting economic and social impacts of introducing children to STEM at an early age, when they are naturally inquisitive and confident in their abilities [5,31–37]. Previously, computer science and engineering were also considered too complex for very young children, but research shows that children as young as age 4 can learn foundational skills of engineering design and computational thinking, when educational supports are designed to be developmentally appropriate [1,2]. Today many countries mandate computer science and engineering education in schools starting in Kindergarten, and life science has been taught to this age range for decades already [9,22,23]. Biodesign is a cross-cutting discipline that integrates science, technology, and engineering in developing solutions to problems that humans face every day. is real-world interdisciplinary experience is critical for children's meaningful engagement with STEAM fields [2,33,37].

The primary challenge with biodesign education is that most of the processes happen at the microscopic level. Children must rely on powerful imaginations to conceive of even the most fundamental concepts, leading to the curricular challenge of how to present meaningful and accurate representations of biodesign processes. New technologies offer novel ways for children to engage with previously inaccessible models and metaphors. Papert famously argued that when children use technological tools to design and create content, the interaction transforms from a passive learning environment to a personally-directed one [26]. He also coined the term, "tool-to-think-with", meaning a physical manifestation that children can manipulate to learn about relationships and ideas and argued that tangible technologies leverage children's natural inclination to learn by doing [26]. In the current study, we explore the possibility of using a novel tool-to-think-with, specifically the tangible CRISPEE prototype, to introduce children to models of gene editing, using a creative design process, tangible materials, and an engaging learning context rooted in coding logic and bioluminescence.

2.1. Research question

This study is part of a larger NSF-funded project called "Making the Invisible Tangible", (grant no. CHS-1564019) intended to iteratively design and research a technology and learning intervention to introduce concepts from biodesign to young children. Earlier work addresses the initial development and user testing of the CRISPEE tool in informal learning spaces, and the resulting design modifications to the tool [38–40]. The main research questions driving the current design study were: (1) how do young children interact with the CRISPEE technological prototype, and (2) what, if any, prior knowledge might the average child bring to a biodesign activity?

Following earlier studies, we concluded that children could learn the basic functions of CRISPEE within 30 min of play-time, and that a handful of children had prior exposure to biodesign concepts that we had not anticipated. We wondered if this might be caused by our homogenous sample of volunteers from families affiliated with or supportive of our research groups. This led to a directional shift in the current study toward a larger, broader sample of children. We scaled the study activity and measures to hone in on children's experience and understanding of CRISPEE and one relevant biodesign concept (genes), while simultaneously broadening our participant population to include a convenience sample of children and families attending a children's museum. We reasoned that by diversifying the participant population, we would arrive at a more realistic view of what the average child would take away from an experience with the CRISPEE technology.

This study explores children's interactions during a play session with CRISPEE, in order to identify how children's interactions with the technology and any prior experience with the biodesign concept of genes could inform their understanding of the metaphors that CRISPEE represents. In the following section, I describe the design-based methodological approach guiding the implementation of this study.

3. Method

The current study describes one user study that was part of the development and evaluation of a new technology and intervention designed to support specific learning outcomes. Design-based research methodology (also called DBR or design research) places an inherent emphases on the integration of research and practice to contribute to the development of novel learning interventions [41–45]. In order to clarify this method, it is helpful to describe the theoretical and epistemological orientations that characterize design research. Following this, we describe how we used DBR approaches to address our research questions.

Learning scientists [41] outline several major features of design research that distinguish it from traditional psychological methods, including a focus on characterizing the context and

Fig. 1. CRISPEE platform (center) and gene coding blocks (front) are used to simulate changing the light color emitting from a bioluminescent animal.

process of the learning intervention, an investigatory model involving large number of complex and interconnected variables, a comfort with iteratively changing the research design to adapt to feedback of the design in the field, and research sites that are frequently located in the "buzzing, blooming confusion of real-life settings where most learning actually occurs" ([41], p. 4). A methodology from the education and learning sciences, DBR represents a departure from more traditional research methods not as a rejection of those approaches, but rather in service of a different research aim, which is to develop innovations that are as useful for their practical applications as for their theoretical contributions [41,42]. Put another way, design studies can be situated as an exploratory stage of the large-scale iterative research cycle that feeds into later confirmatory effect studies [46].

In the current study, DBR was used to investigate the interactions and patterns exhibited by children while working with the CRISPEE tool. This study was deductive in nature, attempting to arrive at a detailed description of how children play with the intervention technology, and so deductive interaction analysis techniques were used [47,48]. Specifically, Erickson's video analysis method was most useful for capturing and characterizing the novel interactions that the learning design was meant to elicit [48,49].

3.1. CRISPEE

CRISPEE was originally conceived as a way to engage children in playful exploration of gene editing, using the model of incubator and accelerator tools for the CRISPR/Cas-9 gene editing system used by professional bioengineers. Pedagogically, CRISPEE is intended as a "tool-to-think-with", a tangible tool that children can touch and build with to learn about relationships between genes and living organisms (e.g. [26,50]). CRISPEE models how biodesigners can alter the light color of a bioluminescent animal (e.g. a firefly), by combining genes that code for fluorescent proteins that glow in the primary colors of light (red, green, and blue).

Fig. 1 shows the CRISPEE kit, including "gene blocks" that can turn each light color on and off, and a platform to build and test gene codes and see the resulting light color. The CRISPEE tool was design to be developmentally appropriate for children in K-2 grades, using a screen-free, text-free, tangible design made of age-appropriate materials such as wood, Velcro, and felt. To use the tool, children select blocks to turn their primary gene colors on (solid-colored block) or off (a block marked with a black X). Children are led through the design process using buttons and LED lights that indicate the three steps of the biodesign process: design gene codes, mix designed sequence into animal's genome, and test the color. After completing the 3-step interaction process (see Fig. 2), the gene block colors they chose will combine according to the physics of additive color mixing (this is color mixing with light, and is distinct from subtractive color mixing with solids like crayons or paint).

Table 1
Demographic information for children in the sample.

	Single child play session n	Pair children play session n	Total n
Age			
4 years	1	0	1
5 years	4	13	17
6 years	7	9	16
7 years	3	7	10
8 years	6	3	9
9 years	3	6	9
Gender			
Male	15	19	34
Female	9	19	28
Group arrangement			
Single	24	–	24 (24 sessions)
Dyad	–	38	38 (19 sessions)
Total			$N = 62$

3.2. Procedure and sample

This study took place at a children's museum setting in the greater Boston area, where CRISPEE was presented as a pop-up style exhibit. Families visiting the museum with children ages 4–9 years were invited to participate in the research study, and completed informed consent procedures. Data were collected from N = 82 children over the course of 6 visits the Boston Children's museum that all occurred between November 2018 and February 2019 during holidays and/or weekday evenings.

During visits to the exhibit, children engaged in their first hands-on play session with CRISPEE. Video footage and field notes of children's physical interaction with CRISPEE were collected. Play sessions typically lasted between 10–15 min. During these sessions, children were first asked the open-ended questions, "Have you ever heard the word 'genes'? Can you tell me what you think that means?" to determine their level of experience with a foundational biodesign concepts. Researchers would spell the word out on paper for them to see. After answering the questions, children were invited to build and test a functional program with CRISPEE. They had the option to work alone or in teams of two during these play sessions. Two researcher were present during all sessions, with one interacting directly with the child(ren) and the other collecting video records and field notes.

Fifty-eight play sessions representing $N = 82$ children were collected during museum sessions. Inclusion criteria for play sessions required that children's birthdates were listed on consent forms to verify that they were in the target age range of 4 to 9 years old. Additionally, children must have engaged with the CRISPEE tool for at least 10 min in the same group structure (e.g., sessions were excluded if they started with one child and a second child joined halfway through, but not if both children were present for the initial 10 min). After removing cases where these criteria were not met, the remaining data comprised 42 sessions representing a final sample of $N = 62$ children (see Table 1).

Of the 19 dyads (comprising 38 children in the sample) 11 were sibling pairs, 4 pairs were friends or classmates prior to participating in the study, and 4 dyads were children who did not know each other, but volunteered to pair with another child who

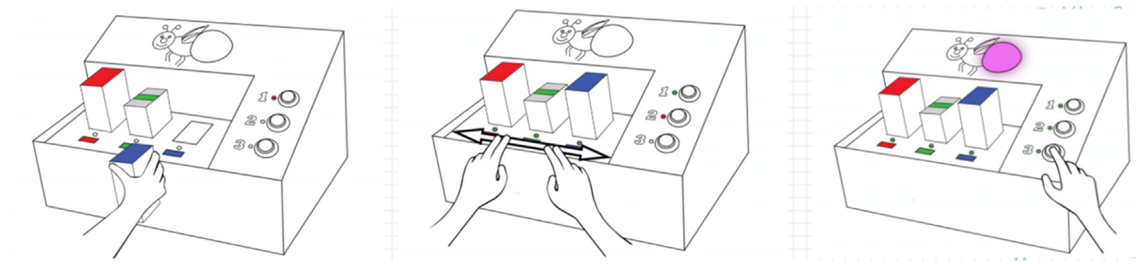

Fig. 2. Three-step CRISPEE interaction.
Source: Reprinted with permission from Verish et al. [40].

was also waiting to play (all individual children who attended the pop up were offered this opportunity, but 24 chose to work alone). Seven (7) dyads were comprised of two boys, 6 were two girls, and 8 were one boy and one girl.

Throughout individual and pair sessions researchers prompted children at the beginning of play session to try anything they wanted. If children in pairs seemed to stay in one partner role (e.g. program builder) for longer than 2 play tests, researchers suggested to children to take turns and swap roles. In most cases, children complied and swapped back after one play turn, and researchers would wait 2 play tests again before prompting. Researchers also prompted to find out children's plans before a test, learn their guesses and explanations about what happened after a test, and before the last test in every session, to invite children to choose a specific color to try to make (if children did not take up this invitation, no further prompting was offered).

During play sessions, parents and guardians representing 44 children (70% of the sample) completed a voluntary survey to gather information about their child's home and school experiences with science, engineering, technology, ethics, and design. Per parent report, 4.5% ($n = 2$) reported holding a trade school degree, 22.7% ($n = 10$) held a bachelor's degree, 70.5% ($n = 31$) held a degree beyond a bachelor's, and 2.3% ($n = 1$) chose not to answer. Nine children (20.5% of the sample) had a family member in a bioengineering or biotechnology field. Forty-two parents also responded to 3-point Likert-style the question, "Have concepts of genes, DNA or related biology topics been introduced at home?" Responses were roughly evenly split, with 18 families (40.9%) selecting 0 ("Not at all") and 21 families (47.7%) selecting 1 ("Somewhat"). Three families (6.8%) selected 2 ("Yes, thoroughly"). Overall, the results of this survey show that the sample of families who responded to the STEM background survey were highly educated (over 93% of the sample earned a bachelor's degree or higher), and around one-fifth of the sample had some kind of family connection to a bioengineering field.

4. Analysis

A research team of six graduate researchers, a post-doctoral researcher, and a research professor from the DevTech Research Group met three times to explore the video data for evidence of children's engagement with sequencing, sensemaking, and ethical design while using CRISPEE. Following Erickson's (2006) four-step inductive interaction analysis method, we first engaged in a deductive analysis of the entire data corpus to arrive at our "communicative/pedagogical functions of research interest", then exhaustively tabulated and visualized the frequency of these events of interest in the transcripts and footage. We used time-sampling to inclusively code for all instances within 15-second segments of time in the first 10-minutes of each session. After several rounds of revision and comparison among the research team, the codebook was refined through unanimous agreement about coding definitions, examples, and inclusion/exclusion criteria. Rater agreement using Krippendorf's alpha was achieved at $\alpha = 0.940$, well above the recommended agreement of $\alpha \geq .800$ ([51], p. 87). Finally, we used the coded data to characterize children's interactions through narrative descriptions ([48], pg. 186). To address the question, "How do children play with the CRISPEE technological prototype?" we followed Erickson's (2006) recommendation to use video and transcript data to create detailed descriptions of what various CRISPEE play interactions look like in practice. The outcome of interest was the proportion of time that each child spent on specific interactions (codes) in their session, and particularly the ways that interactions signified children's understanding of the function of CRISPEE coding blocks.

5. Results

5.1. Children's CRISPEE interactions

$N = 62$ children participated in the CRISPEE play session. The research team coded all 43 play sessions, including 24 in which children worked individually with CRISPEE and a participant-researcher, and 19 partner sessions in which children worked in pairs with a participant-researcher. Interaction over time was explored as a way to learn what aspects of CRISPEE engagement were enticing to children in the first few minutes of exposure, in order to determine if interface changes were required. These interactions showed how frequently children successfully coded a light, versus how many and what type of unsuccessful interactions were common among children in our sample. These patterns in non-functional interactions (e.g. building a tower instead of a program with coding blocks) offered insights about how children conceived of the CRISPEE task, which we interpreted as an indicator of their engagement with CRISPEE as a tool-to-think-with.

On average, children working individually spent around one-third (36%) of their 10-minute play session exploring the CRISPEE interface, including building with blocks in front of CRISPEE, touching the buttons and light elements, and examining the interior electronics of the kit (see Fig. 3). Children spent approximately a quarter (23%) of their time building programs with CRISPEE, one-fifth (18%) of their session testing functional and non-functional programs, and another quarter (22%) of their time conversing with the researcher.

On average, children working in pairs spent just under half (44%) of their 10-minute play session negotiating or collaborating with their partner, and responding to researcher prompts to elucidate their thinking (see Fig. 4). In addition to engaging in peer interactions, which individual play participants did not do, children in groups engaged in much more researcher prompting. This is because in addition to regular prompting for clarification of children's ideas, researchers needed to prompt

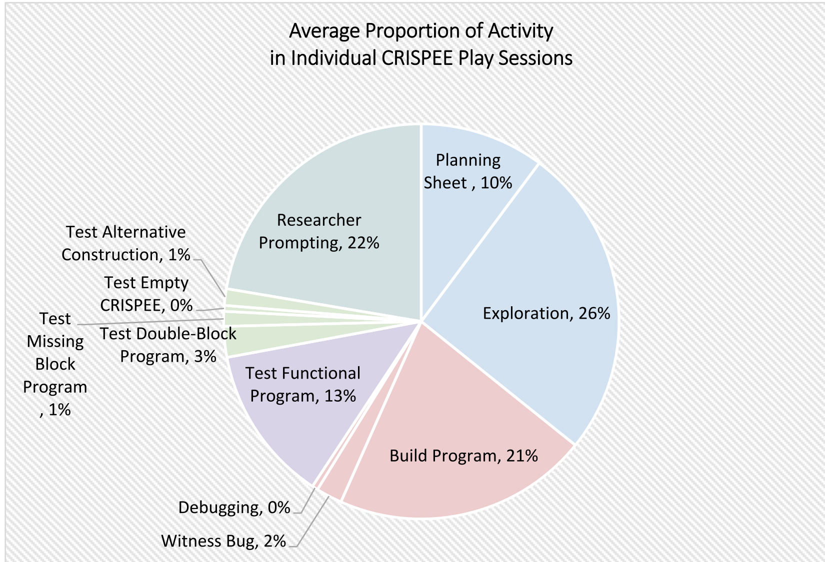

Fig. 3. Average proportion of coded activity for children in individual CRISPEE play sessions. Colors of the pie slices coordinate with the colors of code categories in the codebook.

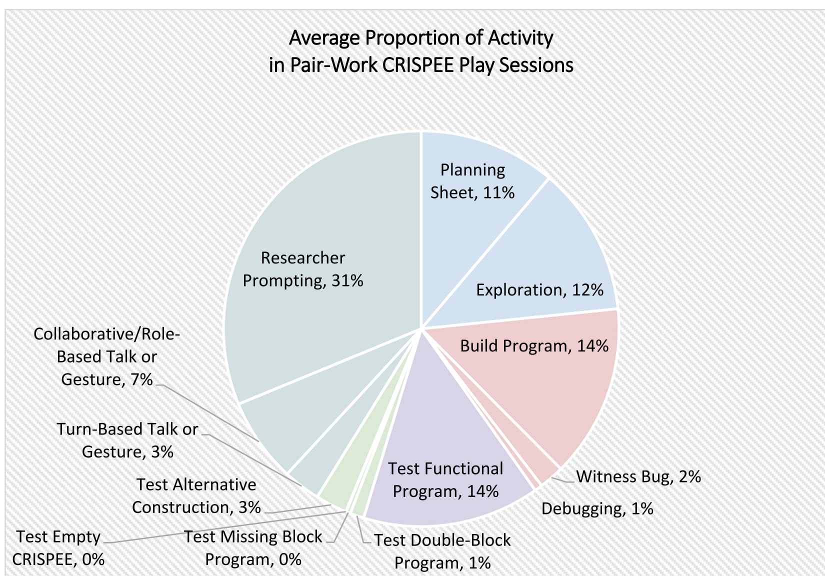

Fig. 4. Average proportion of coded activity for pairs of children in CRISPEE play sessions. Colors of the pie slices coordinate with the colors of code categories in the codebook.

more often to clarify differences between each child's thinking, especially when (as often happened) one child predominantly interacted with the technology while the other child observed. Compared with individual participants, children working in pairs spent less time planning programs and exploring the prototype (23%), slightly less time building programs (17%), and roughly the same proportion of time testing functional and non-functional programs (18%). Additionally, individuals and pairs spent roughly the proportion of time testing functional program (13% and 14%, respectively) to non-functional program (5% and 6%). In looking at types of pairs (siblings, friends/classmates, or strangers), there was no obvious pattern that emerged in describing children's play-roles over time, within or across groups. For example, in one pair dyad of two sisters (aged 7[8] and 5[2]), the younger sibling was more often the "driver" of play acts, taking more turns to build and test programs, while the older sister spent more time collaborating/supporting play. In comparison, another pair of sisters (aged 7[4] and 5[9]), played very equitably, collaborating almost lock-step throughout the activity, with the older child taking on more active role in button-pressing (testing programs). Taken together, partner play seemed idiosyncratic to pair-child social dynamics.

5.2. Children's ideas while playing with CRISPEE

Researchers coded all behaviors in a single play session for each child, then explored for trends. From children's talk and interactions, four main categories emerged of children's ideas about how CRISPEE functioned (see Table 2). Most children exhibited different ideas at different times during a single play session, altering their ideas based on evidence from their most recent tests.

Children held an incorrect idea for an average of 2–4 tests before moving on to another one, although this number depended

Table 2
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 – May also predict that On and Off blocks cannot be mixed (e.g. says they are "different languages")	– Tests programs with same blocks in different order multiple times – 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 – Predicts that mixing On and Off of same color will make "more" of that color – predicts that X blocks will affect hue (lightness/darkness) of light	– Leaves empty slot (rather than adding X) – Attempts to debug a correct "off" program, expecting to see light – Tests programs with both On and Off blocks of same color
(C) **X blocks inhibit** color* *the correct idea for CRISPEE functionality	– Predicts that X blocks affect light by removing or decreasing light – 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 – Tests programs with one of each of the three colors – Does not mix On and Off of same color in one program
(D) **Something else** other than the blocks controls light color	– Predicts that feedback lights relate to block color (e.g. red light means add a red block) – Predicts that one location or slot activates light differently (e.g. "this slot is stronger") – May also predict that On and Off blocks cannot be mixed, or must be mixed in a certain proportion (e.g. "it only works when we use one X")	– Tests alternative (e.g. upside-down, stacked) block configurations – Tests other interactions besides blocks (e.g. buttons, animal faceplates)

Note. Reprinted from original by Strawhacker et al. [38,39].

on the kind of tests they were attempting to run. Because it took the average child 5 min to complete 2–4 tests, children's codes were explored for their *most dominant* idea during the first half (minutes 0–5) and the second half (minutes 6–10) of a 10-minute play session. We looked for the "most dominant" idea since each child might hold more than one at a time, or switch between them rapidly, so we assigned children the idea that they showed the *most* evidence of during the 5-minute increment. The resulting data showed children's main idea when first playing with CRISPEE, and their main idea after collecting evidence from playing with CRISPEE for several testing rounds. In the following section, we describe examples of each idea in practice, using a variety of participant transcripts as examples.

5.2.1. Idea A: Sequence matters

Some children hypothesized that they could change the color of CRISPEE's light by re-ordering the same three blocks. The most common evidence of this idea was when children created the same light color multiple times in a row during their testing session. Of the total 62 children, 17 attended to sequencing during the first five minutes of their play with CRISPEE. This idea typically extinguished after repeated tests yielded the same color light, and only five children maintained this idea beyond the first 5 min of playing. The most consistent signal that children held the sequencing idea was that their first few tests made either a White or Off light. Table 3 shows the tests that one boy (aged 6[1]) completed in his first 5 min of playing with CRISPEE. Consistent with the sequencing idea, he rearranged the order of the same three blocks and made a white light for his first four tests before exploring the X blocks.

Children sometimes also asserted that the solid and X blocks should not be mixed. For example, one boy, aged 9(11), suggested that the two types of blocks "have different programs" inside of them. Finally, some children offered explanations for pursuing the sequencing idea, such as wanting to make a visual pattern out of the blocks, or recalling prior experiences from school or home with a programming language or other technology that emphasized sequencing.

5.2.2. Idea B: The X blocks add color

Idea B was characterized by children believing that the X blocks would somehow enhance a color rather than turn it off. Eight children held idea B at some point in the first five minutes of their CRISPEE play session, and five children (four of whom were different from the original eight) explored this idea in the second half of their tests as well. Unlike the sequencing idea, most children only explored X blocks adding color briefly before moving on to a different working model.

Children with idea B described X blocks as: making "less [color] than the full color block" (girl, 6[4]); the "little color" that helps the "big color" (boy, 8[4]); or as the "darker color" compared to the brighter solid block (girl, 8[11]). These were usually guesses made before children had tried to use X blocks in a program. Idea B was more difficult to identify using children's program logs because it was not characterized by a specific testing pattern, and because children usually extinguished this idea more quickly than the others. When children tested a "double block" program (containing a solid and X block of the same color), they were usually (but not always) testing idea B. Other common tests included programs with missing blocks. For example, one boy (aged 6[0]) attempted to make a red light by testing a single red block and two empty slots, because he hypothesized that the green and blue X blocks would add a small amount of those colors to his light. Because CRISPEE rejects missing block combinations, these tests were always non-functional and children interpreted the red feedback lights in different ways (some of these are described in the section on idea D).

5.2.3. Idea C: The X blocks inhibit color

Idea C – the correct idea – was the hypothesis that the X blocks silenced or inhibited whatever color showed on their background. Multiple solid block colors mix according to light physics principles. For example, a yellow light is created by combining the primary light colors of green and red, and silencing the color blue with a blue X block.

Unlike the other ideas, which children would take up and later reject, none of the children who adapted this idea ended up rejecting it later on, presumably because it was supported by the CRISPEE interaction evidence. Fourteen children expressed this idea at some point in the first five minutes of CRISPEE play, compared with 34 children by the end of each session. This was the most common idea that children held at the end of a play session regardless of age, gender, or group type (partner or individual), meaning that half of the sample was able to arrive a

Table 3
Play session tests during first 5 min of CRISPEE play, from child with Idea A (Male, age 6[1]).

Test	Time point during 10-minute test	Program Tested	Light Result
1	1:00		White
2	2:45		White
3	3:00		White
4	3:15		White
5	4:15		Off
6	5:15		Magenta

Table 4
Sample responses from child participants explaining the X blocks.

Child sex	Child age, in Years(Months)	Verbal explanation of Idea C
M	5(11)	"The X's mean no blue, no green, no red"
F	5(9)	"X might stop it from making light"
M	6(2)	"This one [block] has an X so it doesn't have this color. No X means it [the color] is in the firefly"
F	7(8)	"I think that it [the light] will be green because these two [red X and blue X] blocks mean off"
M	8(3)	"Even though there's a [green] X which is blocking, it's still making the other colors [solid red and solid blue] into purple. I think it's to teach us that there's more than one DNA inside us to make the entire body"

Fig. 5. Child (Male, 6[1]) engaged in alternative construction with blocks, indicating a D-type Idea.

correct understanding of the CRISPEE mechanics within 10 min of playing with the tool.

The main evidence that children held idea C was that they would successfully test many different colors in a row. During play sessions, researchers prompted children to voice their thinking, usually by asking for predictions about what color a program would make, or asking them to explain or guess what X blocks do in a program. Table 4 shows several typical answers from children with the X-inhibits-color idea.

5.2.4. Idea D: Something else controls color

Throughout testing, children also developed various unique ideas that were unrelated to the color of the blocks. Twenty-three children, 37% of the total sample, held some kind of D-type idea in the first half of their play session. By the second half of the session that number dropped to 16 children, 29% of the sample.

Alternative ideas were rooted in an interesting mix of evidence from the CRISPEE kit and assumptions or prior knowledge about genes and color mixing. For example, one girl (9[3]) saw the X blocks and exclaimed, "Oh wait these are X chromosomes! Maybe it tells if the firefly is a girl or a boy. And maybe these [solid blocks] are O chromosomes!" Other children created structures instead of programs, using extra blocks squeezed into the coding platform and non-technical parts (e.g. paper, LEGO) balanced on the control panel (see Fig. 5). These children offered little or no explanation about a causal mechanism for the light color when asked, making it difficult to test or disprove their hypotheses using CRISPEE. For this reason, D-type ideas were persistent in children who held them.

5.3. Enjoyment and engagement

Finally, regardless of the ideas that children held, every child who participated in a play session was motivated to keep playing for the duration of the required 10 min, often asking for more time. Fig. 6 displays a common reaction of surprise and joy that children often exhibited during their first time programming CRISPEE's light to glow. This joy quickly translated to setting a personally meaningful goal, such as seeing CRISPEE glow in their favorite color. Sometimes this translated to richer engagement with the concepts of biodesign, as in the case of a boy (8[3]) who worked for an extra 10 min after his test session ended trying to understand the function of the X blocks. He said before leaving, "even though there's an X [in my program] which is blocking [the light], it's still making the other colors. Even though it's sort of blocking, it's still making purple. I think it's to teach us that there's more than one DNA inside us to make the entire body". In other cases, the sustained engagement was rooted in dramatic play that may or may not have been related to the concepts presented by researchers. For example, one boy 6(3) stayed several minutes after his test to explore many programs with red and green blocks, narrating a superhero-style story while he worked: "The light is red because of this [pointing to Red Solid block]! The red is trying to defeat the green X". Children were highly engaged for the duration of play session, and all children in the study exhibited imaginative play, storytelling, and creative construction with CRISPEE parts at different times in their interviews. This suggests that the prototype materials afforded children opportunities to exhibit self-direction and freedom within their play experience.

Fig. 6. Two sisters (left, aged 5[5]; right, aged 9[3]) are delighted to see their first light creation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

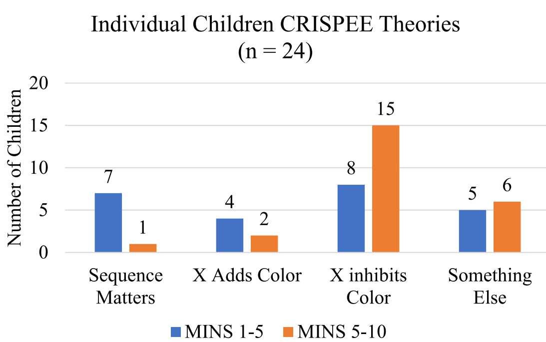

Fig. 7. Individual children's predominant CRISPEE Ideas during the first half and second half of their 10-minute play sessions.

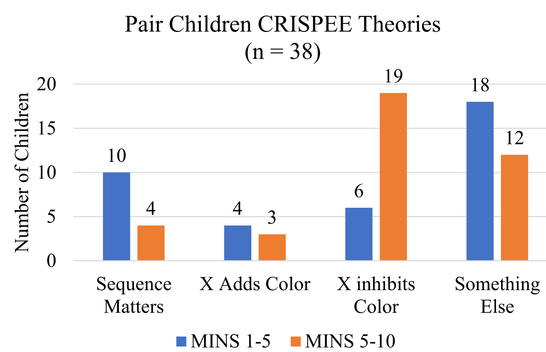

Fig. 8. Pair-work children's predominant CRISPEE Ideas during the first half and second half of their 10-minute play session.

Summary of Interaction Findings

Before playing with CRISPEE for the first time, slightly more than one-fifth of the $N = 62$ children in the study expressed some level of prior familiarity with genes. Throughout play session testing, all children expressed one or more of the four interaction style ideas identified through behavioral coding. Slightly less than half ($n = 29$) of all children changed their starting and ending idea, and the remaining $n = 33$ children held the same interaction idea throughout the entire session. Of these 33 children, $n = 15$ maintained an incorrect idea, and $n = 18$ began and ended their session holding idea C, the correct one. Children aged 6(0) years and younger held more D-type ideas overall, and specifically more ideas related to alternative construction (e.g. building towers out of CRISPEE blocks to change light color). Children aged 9 and older who showed D-type ideas usually expressed prior biology or technology experience to justify their choice. More research is needed to determine if these differences can be attributed to developmental differences, or the convenience nature of the sample.

Figs. 7 and 8 display the proportion of each type of idea that children held during the first and last halves of their play sessions. The major differences between children who participated in pair-work and individual work was that pairs of children showed more exploration of alternative ideas (D-type) in the first half of their play sessions, perhaps spurred by a spirit of playful exploration that occurred with a child partner but not with an adult play partner.

In both individual and pair-work sessions, idea C was the most popular idea by the second half of the session, with 34 children (50% of the total sample) eventually arriving at the correct idea of CRISPEE functionality. However, the proportion of children who ended the session holding the correct idea was higher in the individual sessions (63% of individual session participants) than it was for the pair-work sessions (50% of pair-work session participants). This suggests that children who spent more one-on-one time with the CRISPEE ended up developing more evidence-based ideas and exploring fewer alternative ideas.

5.4. Children's prior conceptions about genes

Of the $N = 62$ children who participated in the CRISPEE play session, 13 children (20.9% of the sample) told researchers that they had heard of genes before, 48 (77.4%) responded no, and 1 (1.6%) did not offer a response. All 13 children who recognized genes offered some kind of definition involving themes of genes as having instructions, information, or messages; genes being

Table 5
Sample of children's responses to the question, "Have you ever heard of 'genes'?".

Child sex	Child age, in Years(Months)	Verbal explanation of genes
M	5(11)	"Babies get mother and father's genes to make hair, skin, eye color. By looking you can't see [them], because genes are inside your body"
M	6(4)	"[genes] give instructions that makes you you"
F	7(8)	"They're little messages in our veins [that] tell us how to look"
F	8(11)	"Genes go into you and make you you. [Genes are] something we get from our mom and dad"
F	9(3)	"[genes] are what makes you you. DNA means that – a strawberry's DNA determines what it looks like and things like that. If you're a girl or a boy you have different chromosomes"

related to family members; and genes being very small, difficult to see, or located inside the body of living things (see Table 5). The 13 children familiar with genes comprised 6 boys and 7 girls, with ages ranging from 5(5) to 9(6), with the median age being 7(6).

Looking at the CRISPEE interactions and ideas of the 13 children with prior gene experience, we found that 9 of them (69%) arrived at a correct understanding of how CRISPEE works (idea C) in the first 5 min of playing with CRISPEE, and 12 (92%) could correctly explain how CRISPEE functions after 10 min of playing. In comparison, 6 (12%) of the 49 children who did not report prior experience arrived at a correct understanding of how CRISPEE works (idea C) in the first 5 min of playing with CRISPEE, and that number climbed to 22 (45%) after 10 min of playing.

6. Limitations

This study was held in an informal learning setting (a popular children's museum in an urban center), and was subject to the challenges of conducting research in naturalistic settings. It was impossible to control for unexpected changes, for example when children left, interrupted, or joined play sessions partway through testing. However, since one of the stated goals of design research is to capture the "buzzing, blooming confusion" of real-life learning settings, ([41], p. 4), these challenges can be re-interpreted as part of the reality of understanding settings and competing demands on children's attention that would occur if they encountered the tool outside of a research context, thus offering context validity to our investigations.

Additionally, the relatively small sample size, the brief learning encounter, and the convenience nature of the sample make it challenging to draw conclusions about how children's prior STEM/biology experience contributed to their understanding of CRISPEE and gene coding learning metaphors, or vice versa. Based on children's voluntary storytelling and imaginative play with the tool, and the importance of prior experience and context in shaping children's engagement with CRISPEE, the next phase of our research will explore how using CRISPEE with framing devices like thematic picture books, dramatic play materials, and early childhood center activities might contextualize and support children's biodesign learning.

Because this was a design study, researchers conducted and participated in all of the play sessions. The fact that, for example, the engineer who built CRISPEE was present during the intervention almost certainly impacted children's reaction to the tool and materials being presented. In future work, we will explore the constraints and opportunities of having regular classroom teachers or informal space facilitators deploy the intervention on their own. In addition to learning which elements of the intervention need to be refined before being used by non-researchers, a major next step is to investigate what kind of educator preparation would be required to help a facilitator feel confident and comfortable to explore the sensitive and complex topics presented in the CRISPEE intervention.

Finally, this study was conducted with a sample of children who had unusually high access to STEM concepts and experiences. Several children in our sample had parents who were themselves professional scientists or engineers A surprising amount of children had prior experience with vocabulary words like "chromosome" (girl, 9[3]) and "heritable trait" (boy, 8[3]), and many also had experience with computer science concepts like programs, robotics, and the engineering design process. The ideas that children surfaced certainly reflect the cultural milieu in which these specific children, in this cultural moment in time and geographic location, understood and interpreted biodesign. Future research should explore the interaction experiences of children with different backgrounds, for example, from rural/agricultural backgrounds that might take a different approach toward animals and ecosystems, or children whose communities hold cultural or religious beliefs about gene editing.

7. Discussion & conclusions

7.1. Reflecting on tangible interactions

During this study, we observed a range of play behaviors that were motivated by roughly four categories of ideas about how the CRISPEE tool worked. These ideas focused on the representational meaning of the coding blocks, as well as the interaction of the blocks within the CRISPEE platform. The conclusion from this work is that after just 10 min of playing with CRISPEE, half of children in our sample were able to arrive at a correct understanding of the meaning of the blocks and their interaction with CRISPEE. A higher proportion of children who worked with the tool individually arrived at the correct interaction idea, compared to children who worked in pairs. All children, regardless of age, gender, or whether they worked alone or with a partner, were motivated to keep playing with CRISPEE, and found it enjoyable and engaging to play with.

Although this work represents an early pilot exploration to develop a science-themed educational technology, the prototype construction directly impacted children's experience of the tool. We aligned our tool construction with design frameworks such as Positive Technological Development [28] by using familiar, child-friendly materials like wood, Velcro, and felt, and designing screen-free tangible interactions. This approach allowed CRISPEE to be sufficiently engaging, safe, and intuitive enough for children to explore on their own, allowing them to arrive more quickly at an understanding of how the tool functions.

In Section 5.1, we reported that partner interactions were idiosyncratic to the social dynamics of children in pairs. In support of this finding, prior research on children's partner interactions during cognitive tasks suggests similarly unpredictable patterns of behavior. In one study of 9–11 year old children engaging in a coding task, researchers found that children's time spent talking (e.g. offering suggestions, requesting a turn) was not correlated with their time spent "driving" the activity, and further, there was no correlation among more one-sided or balanced pair work and quality of finished coding creations [52]. Additionally, the lack of conclusive patterns found in the present study could be attributed to the small size of our sample, and the low number of reference cases in each type of dyad (e.g. our sample only included 3 male–male sibling pairs, 1 male–male friend pair, etc.).

Children working one-on-one with CRISPEE showed overall higher understanding of CRISPEE functionality by the end of the 10 min session, even though pairs and individuals spent the same proportion of time testing correct and incorrect programs. Since the main difference between dyads and individuals was amount of time spend testing and exploring the CRISPEE interface, this finding suggests that something in the physical interaction of CRISPEE was important for children's understanding of how to use it. CRISPEE's tangible interaction style may have made it difficult for children in pairs to learn about its interactions from simply observing someone playing with it, in contrast to screen-based technologies, like SynFlo (see [4]), which use more visual cues to guide interactions and thus more readily support learning-by-observation. Additionally, children in our target age range are likely still developing skills for collaboration and cooperation, potentially adding a level of cognitive load distracting them from the tangible CRISPEE task [53,54]. Another interpretation is that young children working with partners may be more susceptible to taking up unfounded ideas from partners in play. One study of 162 children aged 5–9 years working in pairs to complete a cognitive task found that children were more likely to succeed if they shared a common understanding of the task, however, children were equally likely to convince each other to take up a correct idea as an incorrect one. Even 8–9 year old children with a "more competent" understanding of the task were shown to "regress" in their thinking when paired with a confident 5-yo partner [55]. Tudge [55] attributes this pattern to children's fluid Zone of Proximal Development (the Vygotskian framework that children learn through social interactions), an adaptive mechanism that allows children to co-develop their understanding of the world through scaffolding from peers (even younger, less competent ones) until they gain enough personal experience to shape or alter socially-constructed ideas. In the context of the current study, children only used CRISPEE for a short time, which did not allow children the opportunity for extended testing and critiquing of ideas brought up by partners. Perhaps given longer play sessions and more constructive adult-scaffolded experimentation (rather than simple prompts to continue playing, which is primarily what researchers offered in this intervention), we might observe pair-work children demonstrating similar levels of understanding as individual ones. This idea is explored in the following section.

7.2. Reflecting on biodesign learning outcomes

We designed CRISPEE to support children's exploration of the domain of biodesign, more specifically gene-programming with bioluminescent animals. However, when we looked for evidence of children using the CRISPEE prototype as a model for gene coding, the results suggest that it is possible for children to understand how to use CRISPEE, but not understand the metaphor of gene editing. Thirty-four children left after 10 min with a fairly comprehensive understanding of the mechanics of CRISPEE's programming blocks. With the current data, it would be difficult or impossible to say how much these children related their CRISPEE interactions to the metaphor of gene-editing, but based on the low proportion of gene-related talk in their transcripts, it seems unlikely that it was majority of the children. This could be interpreted to mean that CRISPEE is not an effective tool-to-think-with for biodesign [26,50].

In contrast to this interpretation, the roughly 20% of children in the sample who did have prior experience with the concept of genes tested fewer non-functional programs and took less time in general to arrive at the correct understanding of how to use the CRISPEE prototype. Although CRISPEE on its own may not be an effective *first* introduction to the idea of genes, it is potentially a useful tool for children with some prior experience with genes to contextualize their CRISPEE play. One interpretation of this finding is that children who already held an idea of genes as instructions for building living bodies were able to understand CRISPEE's "gene blocks" as a kind of coding language, and applied that framing to their play with the tool which allowed them master the interactions of CRISPEE more quickly. The framing of genetics as coded instructions similar to a computer program is already used successfully in biology instruction at the middle- and high-school level (e.g. [4,56]). This suggests that 'coding with genes' may be a useful framing for children to explore simple biodesign modeling, especially given the growing evidence that children as young as 5 years old can meaningfully engage with relevant computer science concepts of sequencing, cause-and-effect, and branching patterns [1,57,58]. In the current study, the connections between genetics and coding were presented nascently within the tool design, but not explained in depth for children unfamiliar with the concept of coding. Although the activity design of intentionally open-ended, interactive, and collaborative play with CRISPEE aligns with prior research on enhancing child-exhibit engagement in museum settings (e.g. [59]), this format is no replacement for a learning environment where an educator collaborates and scaffolds young learners through just-in-time provocation and prompting [60]. Because of this relatively low adult scaffolding and low level of guided prompting (e.g. to experiment with certain code combinations), learners in our sample naturally inclined toward other interactional ways to gather information, primarily physical exploration in all children and peer-talk/observation in pair-work children. Further, research on cultivating design learning in children of this age in classroom settings has found that a landscape of tools and teaching supports to model and extend learning is successful for supporting design thinking [61]. Thus, in our ongoing development of this work we will focus on researching ways that other pedagogical approaches, including more collaborative adult scaffolding, a plurality of complementary tools for designing and "coding" colors, and a diversity of curricular supports, might introduce the foundational metaphor of genes as a coding language. Not only would this help to contextualize the CRISPEE tool for children, but we propose this concept would be a valuable learning goal for any intervention seeking to foster educational biodesign experiences for young children.

More work is required beyond this pilot study to identify ways to introduce concepts from genetics and biodesign to young children. However, this study does align with prior work that suggests tangible technologies may be a fruitful way to engage young children in playful exploration of new STEM content [1,26,62,63]. Additionally, the prior biology knowledge that some children brought to the activity deeply supported their engagement with CRISPEE, suggesting that learning tools about this novel STEM topic would be more effective combination with a framing context for learning. Specifically, introducing the concept of genes as a coding language for living beings, in combination with playful tangible tools that model gene-coding interactions, such as CRISPEE, may to be an effective and developmentally appropriate way to present biodesign to young children.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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