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Young Children's Learning of Bioengineering with CRISPEE: a Developmentally Appropriate Tangible User Interface

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Abstract

Bioengineering represents an interdisciplinary field with the potential to engage young learners in science inquiry and engineering design in the context of real-world challenges. Although children encounter bioengineered products and solutions in their everyday lives, they are not introduced to bioengineering until much later in school, after stereotype threats about STEM engagement have crystallized. The purpose of this paper is to present an experimental tangible tool called CRISPEE and evidence from an intervention with young children who explored CRISPEE in the context of an informal bioengineering curriculum. In this design study, 25 children aged 4–7 years engaged in a 9-h workshop designed to introduce them to foundational bioengineering concepts of gene editing, engineering design, and bioethics. Children's attitudes and content knowledge about life science, engineering, and bioengineering were assessed pre- and post-interventions. Mixed quantitative and qualitative results show that most children entered the intervention with pre-existing ideas about genes and attitudes about engineering and science. Post intervention, children demonstrated increased positive STEM attitudes and content knowledge, especially in the area of science inquiry, and also demonstrated an emerging curiosity about the purpose and effectiveness of bioengineering work, including bioethics. Implications for research and practice are discussed.

Keywords Bioengineering education · STEM education · Early childhood · Tangible user interactions

Introduction

Children today encounter genetically engineered foods, medicines, and household products in their homes and schools. Advances in bioengineering research and policy ensure that this field will become even more prevalent in daily lives, as well as popular culture and media (ISAAA 2016; Nebeker 2002). Despite this, there are very few resources that present bioengineering concepts to children in early childhood. Research shows that with support from developmentally appropriate tangible technologies and teaching materials, children as young as age 4 can meaningfully engage with foundational concepts of novel STEM fields, especially related to fields of life science, engineering, and computer science (Hatano and Inagaki 1994; Clements and Sarama 2003; Bers 2018). An evidence-based bioengineering curriculum beginning in early childhood is needed for children's full engagement with twenty-first century concepts. In the current study, we describe experimental pilot educational interventions using CRISPEE, a tangible user interface technology and accompanying curriculum. CRISPEE was designed to introduce young children in kindergarten through 2nd grade (aged 4–7 years) to foundational concepts of bioengineering, leveraging the intuitive ideas and knowledge resources that children carry into science activities.

The purpose of this work is to present a pilot learning intervention to introduce young children to foundational bioengineering concepts using the tangible CRISPEE technology. Initial results from pilot interventions using this curriculum are described, focusing on children's learning outcomes in key areas of STEM attitudes and content knowledge. Specifically, we address the following research question: What are children's attitudes and knowledge related to science, engineering, and bioengineering before and after a developmentally appropriate CRISPEE learning intervention?

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In the following sections, we first describe the need for a twenty-first century early childhood curriculum that addresses bioengineering, and explore hypothesized learning outcomes. We then go on to describe the CRISPEE tool and intervention framework. Using mixed quantitative and qualitative methods, we explain children's science, engineering, and bioengineering learning outcomes after two implementations of preliminary pilot interventions using CRISPEE. Finally, we interpret results through the lens of developmental theory and learning science. The paper concludes with implications for bioengineering and STEM educators and early childhood technology designers.

Bioengineering as a Learning Domain

Biological engineering, or bioengineering, is a STEM field that combines engineering design practices and computer science principles in the design of living solutions to real-world problems (Endy 2005; Weiss et al. 2001). Bioengineers rely on three engineering principles to guide their design work: modularity, abstraction, and standardization. They also rely on computer science to interpret and design gene "programs," or genetic codes, to execute desired behaviors and traits in bioengineered cells and organisms (Kuldell 2007; Endy 2005). Bioengineering has existed in various forms for the past century and has helped launch technological advances in agriculture, space travel, and medicine (Nebeker 2002). Bioengineering has also permeated mainstream US society, with many pharmacies selling direct-to-consumer genetic tests alongside bioengineered medicines (Nelson and Robinson 2014; Paul and Ma 2011; Robinson 2016). However, despite its rising presence in the USA, bioengineering is not explored in formal education settings until high school at the earliest (National Academies of Sciences, Engineering, and Medicine 2016).

Explorations in informal bioengineering education at the late elementary, middle, and high school levels have yielded promising results regarding student engagement and understanding (e.g., Kafai et al. 2017; Kuldell 2007; Loparev et al. 2017; Okerlund et al. 2016; Strawhacker et al. 2018; Walker et al. 2018). For example, Kafai et al. (2017) engaged high school students in a biodesign activity to "grow" their own artwork in petri dishes using genetically pigmented bacteria. In addition to learning about sustainable manufacturing techniques, students reported higher motivation to explore more synthetic biology after the activity (Kafai et al. 2017). The researchers attribute this high engagement to an epistemological shift resituating science from an inquiry activity to a design-oriented one, allowing students to connect science to making, tinkering, and coding (Kafai et al. 2017). Similarly, high school students who participated in the BioBuilderClub curriculum designed at MIT reported higher interest in synthetic biology, and stronger inclination to pursue related fields of science and engineering (BioBuilder Educational Foundation 2019). In another study, researchers developed a tangible interactive exhibit on synthetic biology for The Tech museum in San Francisco, called SynFlo (Okerlund et al. 2016). They designed SynFlo to engage users of all ages in concepts of biodesign and gene programming, and found that the tangibility and interactive visual display allowed learners (including children age 9 and younger) to engage, collaborate, and explore new-to-them biology concepts in a playful way (Okerlund et al. 2016). In Thailand, researchers conducted a week-long experimental STEAM educational intervention among novice middle and high school students to engage them in exploring the technical and social impacts of biotechnological advancement (Subsoontorn et al. 2018). They found that by engaging learners in open-ended design activities and presenting positive reinforcement for creativity, students with little-to-no prior exposure in bioengineering were stimulated to develop interdisciplinary design projects and motivated to seek other biodesign activities in the future. Taken together, this research suggests that tangible technologies and open-ended learning experiences that situate bioengineering as a collaborative design-oriented practice can successfully engage pre-college learners in positive self-identification with STEM and meaningful learning about bioengineering.

Young Children and Bioengineering

Over the past three decades, research in child development and the learning sciences has confirmed that children are able to meaningfully engage with concepts from STEM fields at much younger ages than previously believed (Bell and Clair 2015; Bers 2018; Brophy et al. 2008; Clements and Sarama 2003; Greenfield 2015). However, to ensure positive outcomes, it is imperative to design developmentally appropriate educational interventions and teaching tools for young children (Bers 2018; Papert 1980). Papert (1980) famously proposed the concept of constructionism to describe how children can learn through building, revising, and sharing digital artifacts that they have programmed to follow rules (i.e., coded projects). He explored this concept by developing his tangible LOGO robot turtle to introduce elementary-aged children to advanced computer science and math concepts, and found that tangible programming with physical objects allowed children to use their knowledge of intuitive physics and kinesthetic body movements to shape ideas about abstract coding concepts. Research with the tangible KIBO robotics kit has confirmed that physical technologies can support young children's programming, engineering, and design learning, as well as supporting their emerging STEM self-identity and confidence (Bers 2018; Sullivan 2019). Further, education research shows that digital technologies can present tangible, concrete representations of abstract ideas, allowing children as young as 4 years to exceed previous expectations in learning foundational ideas from science, engineering, technology, and math (Bers 2018; Clements and Sarama 2003; Greenfield 2015; Wilensky and Resnick 1999).

We hypothesize that as an interdisciplinary field deeply rooted in existing STEM domains, bioengineering can be similarly accessible for young children when presented with tangible technologies as learning tools. Indeed, many of the basic disciplinary ideas of bioengineering are related to concepts already taught in traditional elementary curricula (see Table 1) (English 2017; Kuldell 2007). We propose that the lack of a bioengineering presence in elementary education lies in a lack of evidence-based teaching supports and practice recommendations, and a lack of research focusing on the core learning outcomes that children can achieve through exploring bioengineering (Abell and Smith 1994; Anderman et al. 2012; Appleton 2013; Bers et al. 2013; Johnson et al. 2015). The present study aims to explore these gaps, by presenting pilot experimental teaching supports and investigating pre-to-post change in children's bioengineering-related attitudes and learning.

STEM Attitudes in Early Childhood

Early childhood interest and attitudes about science and engineering are very important for children's long-term engagement with STEM disciplines (Lindahl 2007; Lyons 2006; Maltese and Tai 2010), and longitudinal studies confirm that children often decide against a STEM career path in early or middle childhood

Table 1 CRISPEE connections to learning standards

Bioengineering disciplinary concept[1]	Learning domain	Connection to learning standards[2]
Genetic codes as the underlying instructional language for the building blocks of all living things	Life science	*NGSS K-LS1-1.* Use observations to describe patterns of what plants and animals (including humans) need to survive
		NGSS K-ESS3-1. Use a model to represent the needs of different plants and animals (including humans) and the places they live.
Computer programming can be a metaphor for altering genetic instructions in living things	Computer science	*CSTA K-2 1A-CS-02.* Use appropriate terminology in identifying and describing the function of common physical components of computing systems (hardware)
		CSTA K-2 1A-AP-11. Decompose (break down) the steps needed to solve a problem into a precise sequence of instructions
		ITEEA K-2 3.3.A. The study of technology uses many of the same ideas and skills as other subjects (including life science)
Biological engineering is a field that applies engineering design to living biological materials	Engineering Life science	*NGSS K-2-ETS1-1.* Ask questions, make observations, and gather information about a situation people want to change to define a simple problem that can be solved through the development of a new or improved object or tool
		NGSS MS-ETS1-1. Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions
		ITEEA K-2 3.A. The study of technology uses many of the same ideas and skills as other subjects
Bioengineers design genetic programs that create a desired output	Engineering	*CSTA K-2 1A-AP-12.* Develop plans that describe a program's sequence of events, goals, and expected outcomes.
	Computer science	*ITEEA 6-8 3.F.* New technologies and systems can be developed to solve problems or to help do things that could not be done without the help of technology
		ITEEA K-2 9.B. Expressing to others verbally and through sketches and models is an important part of the design process
Bioengineers use creative story-based framing to plan and evaluate the impact of their genetic designs	Language arts	*NGSS K-ESS3-3.* Communicate solutions that will reduce the impact of humans on the land, water, air, and/or other living things in the local environment
	Social studies	*ITEEA 3-5 5.C.* The design of technologies can impact the environment in good and bad ways
		ITEEA K-2 9.B. All products and systems are subject to failure. Many products and systems, however, can be fixed

[1] Bioengineering disciplinary contexts were rooted in professional-level bioengineering education literature (e.g., Endy 2005; Kuldell 2007; Weiss et al. 2001)

[2] Standards are taken from national K-12 science, technology, and engineering educational frameworks (Bybee 2013; CSTA 2017; Dugger 2009)

(Maltese and Tai 2010; Venville et al. 2002; Lindahl 2007; Lyons 2006; Tai et al. 2006). Early STEM experiences and role models can alleviate the pressures of negative stereotype threat (Cunningham and Lachapelle 2010; Lachapelle and Brennan 2018; Sullivan 2019). Girls and minorities, traditionally underrepresented in STEM fields, consistently show more interest and engagement in STEM curricula that connect to human and societal issues (Burke 2007; Häussler and Hoffmann 2002; Bystydzienski and Brown 2012; Buccheri et al. 2011; Drechsel et al. 2011; Miller et al. 2006). This has positive implications for STEM fields with social impacts and human contexts, such as bioengineering and bioethics. Prior research shows that framing STEM activities within a storytelling context is often a successful way to engage young students (especially girls and minorities) in STEM domains, as it leverages their inclination to focus on the societal and ethical contexts of STEM work (Bers and Cassell 1998; Cassell 1998; Kelleher 2009; Lee et al. 2016).

Taken together, prior research suggests that young children can benefit from engaging in bioengineering educational experiences. The study presented in this article responds to the need for bioengineering education by presenting teaching tools designed for young children, including a tangible technological prototype and a story-based learning context (Bers 2018; Lee et al. 2016; Kuldell 2007). We aim to develop a constructionist-oriented intervention using CRISPEE, a tangible technology that allows children to use their intuitive understanding of the physical world to model gene programming, thus deepening their engagement with abstract and invisible concepts of microbiology and bioengineering (Bers 2018; Papert 1980; Wilensky and Resnick 1999). Inspired by findings among older students, the design of CRISPEE emphasizes an engineering design/maker approach rather than a traditional science observation one, inviting children to creatively explore bioengineering the way they explore other disciplines, through hands-on, self-directed experiences (Kafai et al. 2017; Kuldell 2007). The proposed interventions include story-based curricular framing of bioengineering work, which emphasizes the socially oriented problem-solving nature of the field in order to make it more inclusive to girls and minorities. Thus, drawing upon findings from prior research (e.g., Burke 2007; Drechsel et al. 2011; Miller et al. 2006) and informed by research among older learners (e.g., Kafai et al. 2017; BioBuilderClub 2019), we hypothesize that following a developmentally appropriate bioengineering intervention, young children will show increased positive attitudes toward bioengineering, and related fields of engineering and life science, as well as acquisition of content knowledge in all three domains (science, engineering, and bioengineering). The research question guiding our study is, thereby, "What are children's attitudes and knowledge related to science, engineering, and bioengineering before and after a developmentally-appropriate CRISPEE learning intervention?"

Design-Based Research Approach

CRISPEE was developed based on recent research in human–computer interaction, which shows that novel technologies can foster a developmentally appropriate and playful introduction to science and engineering for young children (Brown 1992; Bers 2012, 2018; Okerlund et al. 2016; Papert 1980; Strawhacker and Bers 2015; Sullivan et al. 2017). Pedagogically, CRISPEE is intended as a tool-to-think-with (Papert 1980), a physical manifestation that children can touch and build with to learn about relationships between genes and living organisms (e.g., Wilensky and Resnick 1999). The learning design encompasses the technological prototype, as well as curricular scaffolds, to engage children in thinking with CRISPEE about bioengineering. The study we present in this article describes our preliminary design and evaluation of the CRISPEE technology and curricular intervention. Our approach draws upon design-based research methodology (also called DBR or design research), which places an inherent emphasis on the integration of research and practice to contribute to the development of novel learning interventions (Barab and Squire 2004; Brown 1992; Cobb et al. 2003; Edelson 2002). It is important to note that design-based research does not necessarily emphasize the iterative design of a *technology*, although that is often part of the work. The focus is more accurately described as iterating on the design of a *learning intervention*, which can include changing the learning goals, intervention setting, or pedagogical approach from one implementation of the intervention to the next. In the current study, we iterated on the assessment measures and instruments, in order to learn appropriate ways to capture young children's idea construction in this novel and untested domain.

CRISPEE Technological Prototype

The design of CRISPEE was inspired by existing tools in biology laboratories, specifically incubator and accelerator tools for the CRISPR/Cas-9 gene editing system. The current prototype was created through an iterative process with input from children and educators (Verish et al. 2018). The goal of the tool is to model how bioengineers can program the color of a bioluminescent organism by selecting and combining genes that code for fluorescent proteins which glow in the primary colors of light (red, green, and blue). The current version of CRISPEE, shown in Figs. 1 and 2, engages children in creating a genetic program that allows a bioluminescent animal (fireflies, jellyfish, deep sea fish) to produce light. The CRISPEE tool was design to be developmentally appropriate for ages in grades K-2: it is a screen-free, tangible platform made of age-appropriate materials to resemble existing equipment found in bioengineering labs. Interaction with the tool does not require reading or inputting textual information.

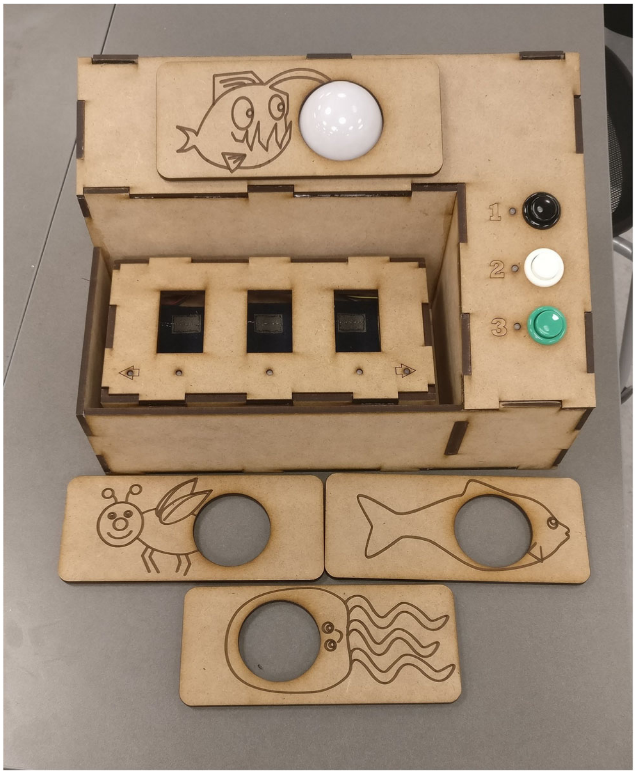


Fig. 1 CRISPEE (v2) tool, shown with extra faceplates. Children can build gene programs with different red, green, and blue blocks to create colors for bioluminescent animals

Children construct a genetic program by combining discrete genes represented with wooden blocks that code for red, green, and blue bioluminescent proteins. Children can "turn on" a color using a large block with a solid-colored top, and can "turn off" a color using the small block with a black X symbol over the color. After constructing the program, children "mix" the genetic program into the cells of the bioluminescent animal by moving the platform back and forth—the physical mixing stage was introduced in order to imitate physical aspects of biological experimentation processes. Finally, children test their program—observing the animal light up in the color coded by the program.

Children are led through the process using buttons and LED lights that indicate the three steps of the bioengineering process: design, mix, and test. Figure 2 depicts the interaction with CRISPEE.

Pilot Learning Intervention with CRISPEE

The proposed intervention consisted of 3-day bioengineering-themed educational workshop programs. Children engaged in several experimental curricular activities as part of the intervention. These included listening to an original picture book—*Adventures in Bioengineering*, about a fictional bioluminescent animal whose light is bioengineered to solve a problem (during a circle read-aloud), and engaging in free play at a variety of STEM-themed centers. The *Adventures in Bioengineering* picture book was developed as a way to present a story-based context to help children understand when and why someone might choose to change genes. The plot follows an anthropomorphic firefly who is born without genes to glow, and subsequently gets separated from the other fireflies. He meets a bioengineer who helps him change his genes and glow in a color of his choice, allowing him to locate his friends again. Throughout the story, vocabulary and concepts related to bioengineering (e.g., genes, engineering, bioluminescence), as well as instructions for how to use CRISPEE, are introduced in a way that is developmentally appropriate and playful (see Figs. 3, 4, 5).

Children were invited to move between centers at their own pace, with participant–researchers nearby to facilitate play as needed. This pedagogical choice was aligned with research on developmentally appropriate practice (DAP), a pedagogical perspective that emphasizes free play and diverse experiences, particularly when introducing novel technologies to children (Ailwood 2003; Yelland 2011). Table 2 outlines children's daily activities during the informal workshop.

During the unstructured playtime, children could choose from engineering, life science, physics, or CRISPEE bioengineering centers (see Appendix A for depth descriptions of activity centers and materials). These centers allowed children to use common lab tools to practice the process of scientific inquiry, such as magnifying glasses, microscopes, beakers, and liquid droppers. At each center, children had the option to wear STEM-themed safety gear, including functional child-sized lab coats, lab gloves, hard hats, and protective ear/eyewear (see Fig. 6). Children were offered freedom of choice in time spent at each activity, in alignment with DAP pedagogy and research for early childhood learning settings (Ailwood 2003; Yelland 2011).

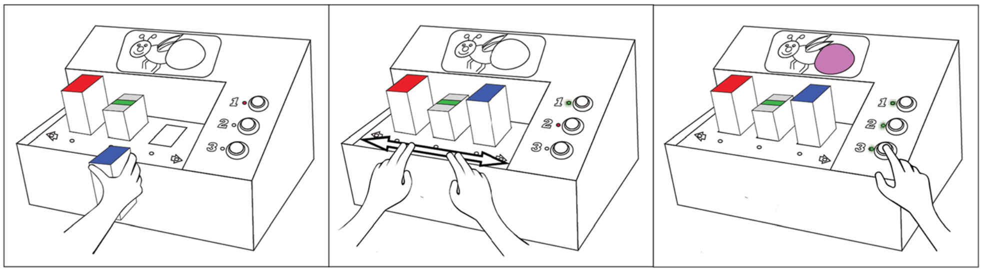


Fig. 2 Three-step CRISPEE interaction (reprinted with permission from original author) (Verish et al. 2018)

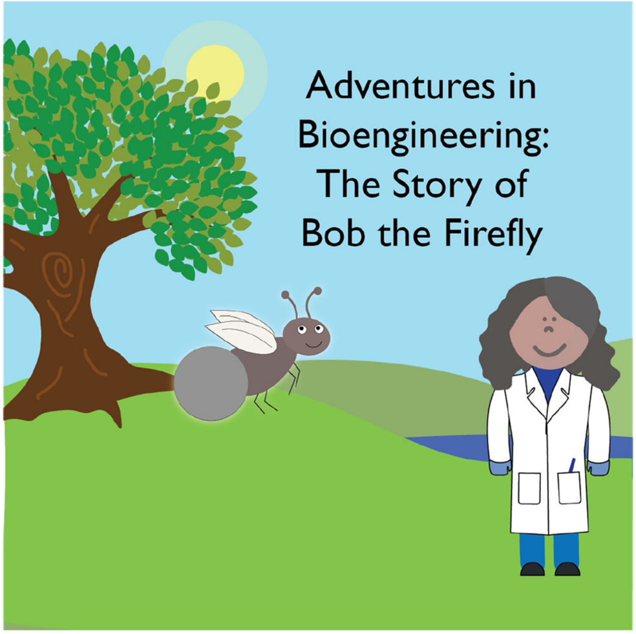


Fig. 3 The cover of the *Adventures in Bioengineering* storybook showing the main character, a talking firefly, and his bioengineer friend

A portion of each workshop day was dedicated to semi-structured or unstructured play with CRISPEE. During the second day of the intervention, children were invited in groups of two or three to work with a participant–researcher and a video recording researcher to have their first play experience with CRISPEE. The participant–researcher prompted children with open-ended questions to verbalize their ideas about the function of CRISPEE's elements, and offered positive reinforcement when children expressed curiosity by inviting them to test their theories. These sessions were child-directed, and different groups focused on different elements of the prototype. For example, some children wanted to build as many light combinations as possible, while others wanted to look inside the prototype and ask about the people who constructed the prototype. After a brief (approx. 20 min) play session, children returned to their other center activities. Once all children had completed their initial CRISPEE play session, CRISPEE was offered as a center activity during the intervention. In contracts to other centers that were rotated throughout the 3-day workshop, CRISPEE was always available as a permanent center option.

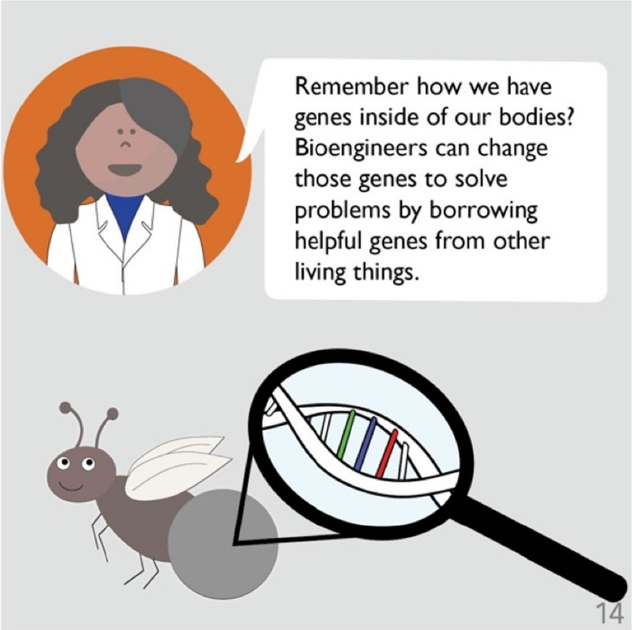


Fig. 4 A page of the *Adventures in Bioengineering* storybook showing an explanation of the concept of genes

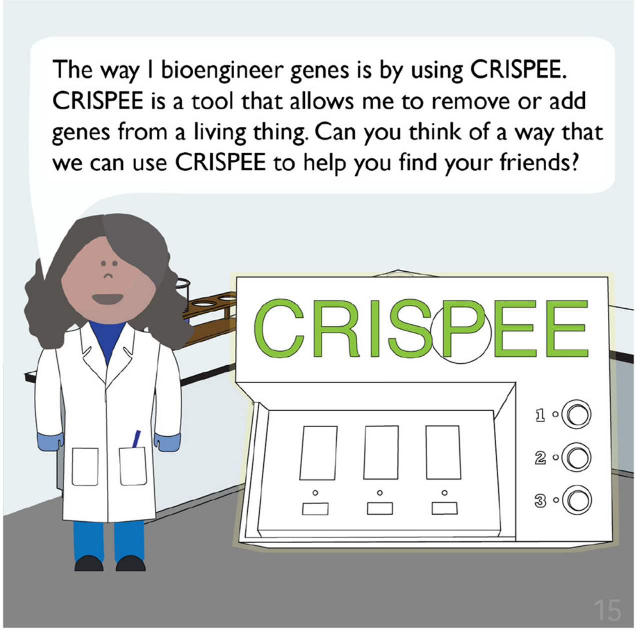


Fig. 5 A page of the *Adventures in Bioengineering* storybook showing an explanation of the CRISPEE technology

Procedure

The study procedure is rooted in design experiment methodology, in which "[scientists] attempt to engineer innovative educational environments and simultaneously conduct experimental studies of those innovations" (Brown 1992, p. 141). Design experimentation supports iterative refinement of the experimental intervention in order to investigate minor changes in learning outcomes. The aim of this approach is to begin developing theories of how and why novel interventions achieve specific learning outcomes (Svihla 2014; Edelson 2002). In the current study, we iteratively explored the designed CRISPEE technology and the curricular context in which it was introduced to address the research question, "What are children's attitudes and knowledge related to science, engineering, and bioengineering before and after a developmentally-appropriate CRISPEE learning

Table 2 Intervention schedule. This table describes children's daily curricular and research activity

	Day 1	Day 2	Day 3
Research activities (researcher-guided 20-min sessions)	Pre-assessments (one-on-one with researcher)	CRISPEE play testing (groups of 2–4 children with one researcher)	Post-assessments (one-on-one with researcher)
Learning activities (child-directed 3-h sessions)	Welcome/get to know you games (large group)	Bioengineering storybook (large group)	Stem centers (groups of 4–6 children)
	Stem centers (groups of 4–6 children)	Stem centers (groups of 4–6 children)	Games and goodbye (large group)

Children temporarily left regular open-ended play centers to participate in brief (20 min or less) research activities

intervention?" For a discussion of the design research phases of the CRISPEE technology, see Verish et al. (2018).

The intervention consisted of 3-day bioengineering-themed educational workshops held free of charge during public school holidays at Tufts University's Eliot Pearson Early Childhood Makerspace. The workshop ran for 3 h a day (a total of 9 h per workshop); Table 2 shows the workshop schedule. The physical environment and schedule of activities resembled a typical US early childhood classroom or recreational center (e.g., Olds 2001; Curtis and Carter 2014). However, all supporting educational and play materials (e.g., picture books, board games, dramatic play clothing) were selected to support children's explorations of bioengineering and related STEM fields. On day 2, children were invited to pause their regular open-ended play centers to participate in brief (20 min or less) research activities—a play session with CRISPEE. During the CRISPEE play sessions, researchers led groups of two to four children through guided play with the CRISPEE tool in a separate room. Both the lead education researcher and lead technology designer were participant–observers in these CRISPEE play sessions. Pre- and post-surveys were administered one-on-one by researchers in a quiet section of the makerspace at the beginning of day 1 and at the end of day 3.

Children in kindergarten through 2nd grade (aged 4–7 years) were recruited to participate in the 3-day workshops. Recruitment emails were distributed through the Tufts University Department of Child Study and Human Development, DevTech Research Group, and Wellesley College Human-Computer Interaction Lab e-lists, which reach a combined total of approximately 5000 voluntarily subscribed families in the Greater Boston geographic area interested in participating in ongoing research. Two implementations were run, and participants were recruited separately for each implementation (using the same e-lists) in order to allow for a design experiment model so that assessment measures could be iteratively adapted from one implementation to the next. The CRISPEE tool and the curricular activities remained the same across both implementations.

Fig. 6 Children wore protective clothing like lab coats and gloves while they played at the science centers throughout study sessions

A convenience sample of $n = 14$ children participated in implementation 1, and $n = 11$ children in implementation 2, for a total of $N = 25$ participants ($n = 6$ girls and $n = 19$ boys). The average participant age, in years;months, was 6;5 (SD = 7 months), with the youngest child aged 4;11 and the oldest aged 7;11 (see Table 3).

Children in our sample represented a range of ages, and included more boys than girls. In an experimental control study, this would represent a limitation in study design. However, as a design-based research study, we focused our analysis on non-parametric statistical tests, meaning we did not aim to draw conclusions from our study to generalize to the larger population. Rather, we focused on within-sample quantitative trends and qualitative descriptive vignettes in order to gauge the impact of the learning intervention on children's performance on assessments. Within-group comparisons by gender would still be difficult due to the larger number of boys relative to girls. However, we consider the fact that voluntary self-selecting families of boys were more likely to register for a bioengineering activity workshop compared with families of girls, an interesting finding by itself. Future research should investigate this differential gender engagement and whether it stems from children's self-reported STEM interest, parent/guardian interpretations of their children's interest or readiness, or some other factors. In future iterations of this design research, we will alter recruitment and registration tactics to actively recruit equal sample sizes of girls and boys.

Table 3 Demographic information for participants in implementations 1 and 2

	Implementation 1		Implementation 2		Total	
Gender	$n_{\text{male}} = 10$		$n_{\text{male}} = 9$		$N_{\text{male}} = 19$	
	$n_{\text{female}} = 4$		$n_{\text{female}} = 2$		$N_{\text{female}} = 6$	
	$n = 14$		$n = 11$		$N = 25$	
Age	Min = 5;5 years		Min = 4;11 years		Min = 4;11 years	
	Max = 7;10 years		Max = 7;11 years		Max = 7;11 years	
	Mean = 6;6 years		Mean = 6;4 years		Mean = 6;5 years	
	SD = 9 months		SD = 1;1 years		SD = 7 months	
Assessments	Pre	Post	Pre	Post	Pre	Post
	Engineering Interest and Attitudes	Engineering Interest and Attitudes	Engineering Interest and Attitudes	Engineering Interest and Attitudes	$n = 25$	$n = 22$
			Science Learning Assessment	Science Learning Assessment	$n = 14$	$n = 11$
			Bioengineering Educational Assessment	Bioengineering Educational Assessment	$n = 14$	$n = 11$

Measures

During day 1 (first activity) and day 3 (last activity) of the workshop, children in both implementations participated in pre- and post-assessments on STEM domain skills and attitudes in science, engineering, and bioengineering. Children's attitudes and knowledge related to science, engineering, and bioengineering were assessed using existing pre-/post-questionnaire–style assessments (see Table 3). In implementation 1, we used an engineering questionnaire validated for use in elementary school settings. We adapted this measure for use with young children, and added two new questionnaires, which we developed to capture science and bioengineering content. In implementation 2, we extended our assessment to include the following: the same validated engineering questionnaire used in implementation 1 as well as an existing validated science assessment, and a new bioengineering assessment modeled on elements of both of the other two measures. The change in the assessment measures between the two implementations was driven by our reflection on findings from study 1. Such change in assessment measures is aligned with the design experiment methodology, which we applied in this study. In the following, we describe the measures used in each implementation in more detail.

Children in our study completed assessments one-on-one with a researcher present. In order to alleviate potential bias in assessing performance, we introduced researchers as workshop "counselors" and "teachers" and allowed them time to free play with children before completing assessments. In this way, researchers were presented as caregivers rather than intimidating authority figures. Children were invited to participate in the assessment "research center," positioning it as additional activity centers like all other activities in the room. We thereby view children's responses as no more biased than they would be in any naturalistic learning setting.

Implementation 1

In the first implementation, we assessed children's attitudes using a measure developed for assessing elementary-aged children's attitudes toward and awareness of the domain of engineering, the Engineering Interest and Attitude (EIA) (Lachapelle and Brennan 2018), and original adaptations of the EIA to capture science and bioengineering attitudes (see Appendix B to view the assessment measures used in implementation 1). The EIA is a researcher-administered questionnaire, which uses multiple choice questions to capture children's engineering knowledge and attitudes. This measure has been validated and found to be reliable with slightly older children (ages 8–11 years) (Lachapelle and Brennan 2018). However, we slightly adapted the language of some items to accommodate the vocabulary of a 5-year-old child (for example, "Engineering is useful in helping to solve the problems of everyday life" was changed to "Engineering is useful in helping to solve problems").

To capture children's subjective attitudes about science and bioengineering, we adapted items from the EIA to address these separate domains. In general, these changes were minor and mainly involved changing the word "engineering" to "science" or "bioengineering." Assessment items were presented as opinion statements with Likert-style agreement scales. Researchers read aloud statements and asked children if they understood or had questions about the statement, and how they felt about it. Children responded using a 1–5 Likert-style scale, with 1 being strongly disagree and 5 being strongly agree. All items were positively balanced, such that low-scoring items always correspond with negative attitude scores. Because the original EIA was adapted from its original test conditions and the science and bioengineering assessments were original instruments adapted from the EIA, the reliability and validity of these measures is untested and results should be interpreted with caution. We used the same measures both pre- and post-assessments in order to capture changes in attitudes following the intervention.

Implementation 2

In the second implementation, children completed the adapted EIA to capture engineering attitudes, in addition to the validated Science Learning Assessment (SLA) (Samarapungavan et al. 2009), and an original Bioengineering Educational Assessment (BEA) that we modeled on elements of the EIA and SLA (see Appendix C to view the assessment measures used in implementation 2). The SLA contains 24 items designed to capture kindergarten students' "understanding of science inquiry processes and life sciences concepts," and has been validated with kindergarten-aged children (5–6 years) (Samarapungavan et al. 2009). In contrast to the EIA, which focuses on self-report attitudes and interest, the SLA focuses on learning and understanding of common preschool and kindergarten science topics such as camouflage, properties of living organisms, and solving problems using observations to gather evidence.

To capture bioengineering learning, we developed an original Bioengineering Educational Assessment (referred to from here as BEA) modeled on the attitude items of the EIA and the content items of the SLA. When developing bioengineering items, we focused on presenting visual answers to multiple choice questions, and content topics focused on genes and bioluminescence, per the learning metaphors used in CRISPEE. Sample bioengineering questions included "Which of these things has genes?" (see Fig. 7), "Which of these differences is caused by genes?" (see Fig. 8), and "One of these sheep has been bioengineered. Do you know which one?" (see Fig. 9). The original SLA was found to be valid and reliable with a test population similar to that in the current study (Samarapungavan et al. 2009). However, as the bioengineering assessment is an original instrument adapted from the SLA, and the engineering assessment used was adapted for a different population than the original EIA (Lachapelle and Brennan 2018), the reliability and validity of these measure is untested and results should be interpreted with caution.

Data Analysis

To score open-response questions, researchers coded whether the responses sufficiently reflected the definitions of bioengineering concepts introduced during the CRISPEE intervention. Two raters judged responses against a predetermined acceptable answer or set of answers. Cohen's κ tests were run on each item to determine agreement between the two researchers' judgements on four open-response bioengineering items and one engineering item from the pre- and post-assessments (test results are reported in the "Results" sections). To reduce bias, the primary rater and other raters discussed any items where there was disagreement and arrived at a final agreement rating of each item (Landis & Koch, 1977). The results presented here reflect these iteratively rated scores.

Quantitative analysis of assessment scores involved descriptive statistics to explore all individual measures. Many questions were dichotomous categorical variables (e.g., "True or False"), and several open-ended questions were also coded dichotomously to simplify analysis (e.g., "correct or incorrect"). Due to the naturalistic intervention setting, children's attendance was inconsistent across intervention days. Thus, response samples for each item ranged from $n = 8$ to $n = 11$ depending on the question and the implementation. Due to this small sample and the dichotomous nature of many variables, non-parametric tests were used to determine evidence of pre-to-post change within children's responses. Wilcoxon signed-rank tests were used to determine significant pre-to-post change for 5-point Likert-style scaled items. Exact McNemar's tests were applied to dichotomous variables (such as open-response items marked "correct" or "incorrect") to determine differences in the proportion of correct responses before and after the intervention.

Results

In the following sections, we first report on trends from the CRISPEE intervention and quantitative findings from the pre-/post-assessments used in implementations 1 and 2. We then describe qualitative findings from the two implementations to contextualize the results.

CRISPEE Interaction and Learning Intervention Findings

In both implementations, children were highly engaged with the curricular centers offered throughout the intervention, particularly the STEM-themed clothing and equipment. Children clearly associated these clothes with STEM professions, since their dramatic play while wearing them centered on science sub-fields such as paleontology and microbiology. This kind of embodied play suggests positive engagement with a STEM self-identity.

While playing with CRISPEE during choice times, children mainly practiced the interactions of programming a light in the color of their choice to glow from a bioluminescent animal such as a firefly. Children employed inquiry strategies of repeating the same program multiple times or mimicking a friend's pattern to see if they would find the same results; changing one single block at a time to determine the effect on the outcome; and calling adults and peers to assist in moments of confusion. A majority of children were able to master

Fig. 7 Multiple-choice image responses to the BEA item: "Which of these things has genes?"

the core interactions of CRISPEE after a 20-min play sessions with researchers (see Fig. 10). Seventeen children out of the total 25 correctly explained that the CRISPEE blocks were representations of genes or instructions inside of an animal's body. Ten were able to predict the light color that a given program would create.

Implementation 1

The first implementation was a pilot trial for running the curriculum and for the attitude assessments with children. These findings altered our approach in implementation 2. Results are presented below.

Pre/Post Attitude Findings

Children in implementation 1 responded to 4 pre/post questions each about their *science*, *engineering*, and *bioengineering attitudes* for a total of 12 attitude questions. Overall scores were computed by summing responses to the four questions in each of these domains, to arrive at overall total and mean scores for positive attitudes toward science, engineering, and bioengineering (see Table 4).

Non-parametric Wilcoxon signed-rank tests were conducted to compare children's attitudes before and after the intervention. The first implementation of the CRISPEE intervention did not elicit a statistically significant change in children's overall bioengineering attitudes ($Z = -1.156$, $p = 0.248$, $n = 11$) or overall science attitudes ($Z = -0.949$, $p = 0.343$, $n = 7$). However, overall engineering attitudes showed significant increases pre to post ($Z = -1.997$, $p = 0.046$, $n = 11$). Of the 12 individual attitude items, only two showed significant differences pre to post. These were the engineering item "Engineering is useful in helping to solve problems" ($Z = -2.232$, $p = 0.026$, $n = 11$) and the science item "I would enjoy being a scientist when I grow up" ($Z = -2.058$, $p = 0.040$, $n = 11$), and no bioengineering items. No differences were found across age or gender. For non-significant items, children in the sample showed overall neutral or positive agreement with all of the statements both before and after the intervention.

Pre/Post Content Knowledge Findings

Children in implementation 1 responded to 11 total pre/post *content knowledge* questions: three were about bioengineering, four were about science, and four were about engineering.

Of the three bioengineering items, McNemar's tests revealed that only one of them showed a significant difference in the proportion of correct answers pre to post. The question "What is a gene?" ($n = 11$, $p = 0.031$) showed a significant increase in correct responses, while the questions "What is bioenginering?" ($n = 11$, $p = 0.250$) and "What is a biobrick?" ($n = 11$, $p = 1.000$) did not. In fact, the question about the vocabulary word biobrick (a genetics term for a gene with a known phenotype or outcome) yielded such low understanding in post-tests that the researcher team agreed to remove this

Fig. 8 Multiple-choice image responses to the BEA item: "Which of these differences is caused by genes?"

Fig. 9 Multiple-choice image responses to the BEA item: "One of these sheep has been bioengineered. Do you know which one?"

vocabulary word from future implementations as it seemed developmentally inappropriate for children aged 5–8 years.

Children showed no significant improvement in any of the four engineering items or the four science items. This is likely due to the fact that children in implementation 1 had relatively high exposure to both engineering and science prior to the intervention. For example, over half of the sample ($n = 6$) correctly defined engineering as building or making things prior to the intervention. From this result, we can conclude that children in our sample were exposed to engineering outside of the study context.

Implementation 2

Findings from implementation 1 suggested that children already had prior exposure to engineering and science, and very limited or no exposure to bioengineering. Despite this, attitude scores showed high positive feeling toward bioengineering, higher in some cases than engineering and science, with which children were more familiar, suggesting possible inflation of scores based on the novelty of terms used. The research team agreed to adjust the assessments for implementation 2 to focus more specifically on content knowledge in the three domains before and after the educational intervention, which was largely unchanged from implementation 1. To this end, a validated science knowledge measure, the SLA was introduced. The bioengineering assessment was adapted based on the style of the SLA, in the same way that some attitude and content items were modeled on the EIA in implementation 1. Students responded to 35 total matched pre and post items (see Appendix C).

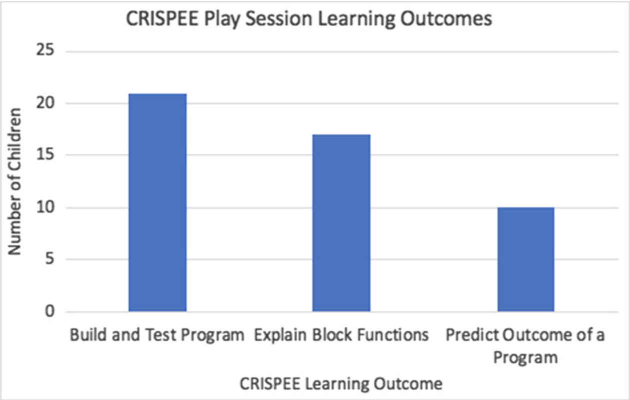


Fig. 10 After a brief play experience with CRISPEE, a majority of children in our sample were able to master the tangible interactions ($n = 21$) and explain the function of specific blocks ($n = 17$)

Pre/Post Attitude Findings

Children responded to four (4) engineering attitude items, taken directly from the validated engineering attitude assessment (EIA). A non-parametric Wilcoxon signed-rank test showed that implementation 2 CRISPEE intervention elicited a statistically significant change in children's attitude toward the engineering item: "Engineering is useful in helping to solve problems" ($Z = -2.565$, $p = 0.010$, $n = 11$). However, no significant pre-to-post change was shown for the other three attitude items. As in implementation 1, this lack of change is likely due to the high scoring nature of children's engineering attitudes at pre-testing. For example, all three non-significant attitude items averaged a pre-test agreement score of 3.8 or higher out of a possible score of 5, which was sustained in post. The significant item about engineering being helpful to solve problems showed an average pre-intervention score of 3.1, which increased post-intervention to an average score of 4.4.

Pre/Post Content Knowledge Findings

Children responded to a total of 31 content knowledge items in implementation 2, consisting of three engineering, nine bioengineering, and 17 science items.

Exact McNemar's tests showed no significant change for any BEA (bioengineering) items except for one: "Which is these differences is caused by genes?" ($p = 0.031$, $n = 10$). In contrast to implementation 1, children in implementation 2 did not show significant pre-to-post change for the question: "What is a gene?" This is perhaps explained by the fact that children in the second implementation started with a higher

Table 4 Descriptive statistics for implementation 1: child agreement with positive attitude statements about engineering, science, and bioengineering

Attitudes		*N*	Overall Min	Overall Max	Overall mean score	Overall SD	Item mean score	Item SD
Biongineering	Pre	14	10.00	20.00	15.00	3.35	3.75	0.84
	Post	11	10.00	20.00	16.91	3.59	4.23	0.90
Engineering	Pre	14	8.00	20.00	16.36	3.91	4.09	0.98
	Post	11	11.00	20.00	17.82	3.06	4.45	0.77
Science	Pre	7	6.00	20.00	16.14	4.81	4.04	1.20
	Post	11	11.00	16.00	14.36	1.86	3.59	0.46

Scores were based on a 1–5 Likert-style scale, with 1 being "strongly disagree" and 5 being "strongly agree." The maximum possible overall score was 20, and the minimum possible overall score was 4

SD standard deviation

average understanding of genes at baseline ($M = 0.23$ out of 1.00, SD = 0.47) compared with first implementation children, who had no prior exposure ($M = 0.00$ out of 1.00, SD = 0.00). Despite the lack of significant change, children showed incremental improvement in correctly answering bioengineering content questions from pre- to post-assessments (see Fig. 11). Children performed relatively better on multiple choice pre and post items that depicted bioengineered organisms (i.e., bioluminescent animals), and relatively worse on pre and post items about describing or defining practices of bioengineering. There was only one question that *all* children correctly answered after the intervention. The question prompt was, "Bioengineers need to make this sheep glow. Which of these sea creatures has the genes that bioengineers need?" Researchers showed two images of non-glowing fish, and a third image of a bioluminescent fish. Children performed very well on this question both before and after the intervention, likely due to the obvious visual clue of the glowing fish. Interestingly, in post-tests, four children also asked unsolicited follow-up questions such as, "Why do the bioengineers need to make the sheep glow?" (boy, age 6;5) and "What are they going to do with the glowing sheep?" (boy age 6;8). No children asked such questions during pre-tests. In later sections, we will discuss the possible implications of this finding. Despite a general improvement in scores for bioengineering questions, few of the pre- to post-test differences were statistically significant. In one question, $n = 11$ children were shown three images of children with differences (different clothing, favorite sports, and eye color) and asked to identify which difference was caused by genes. Children were significantly more likely to answer this correctly in post-tests ($p = 0.031$), with 13% of children correctly choosing the image with different colored eyes in pre-assessments, and 36% choosing correctly in post.

As in implementation 1, there was no significant change pre to post on the other engineering items.

McNemar's tests for children's responses to the validated SLA assessment showed no significant pre-to-post changes for any science items. As with implementation 1, non-significant pre-to-post changes in science and engineering items can perhaps be attributed to high content knowledge in these domains at baseline. For example, the average overall SLA score for a child in implementation 2 was 12.8 out of 17 at pre-tests and 13.1 in post-tests. Children performed best on inquiry item 1, a question that asked children to identify which activity was a science activity, and life science item 8 (choose the thing that would need air to breathe). Other high-scoring questions were life science item 3 (choose the leaves that would camouflage an orange butterfly) and inquiry items 7–9 (choose the tools that help with specific science tasks). Conversely, children performed worst on two questions that asked children about observing and hypothesizing about properties of living things. Overall, there were very little changes on each item from pre to post, and any differences were non-significant (see Fig. 12).

Finally, researchers asked children in pre-/post-tests if they could describe a way that bioengineering was similar to science and similar to engineering. Twenty percent of children correctly described a similarity between engineers and bioengineers (e.g., "they both build things") in pre-tests, compared with 50% in post-tests. Additionally, 30% of children in pre-tests and 40% in post correctly named similarities between bioengineers and scientists, such as "They experiment with things" (girl, 7;8), "They both explore bio. Bio is things that are alive" (boy, 6;1), and "They help people" (boy, 4;11). Despite these pre-to-post increases, McNemar's tests revealed no significant difference in the proportion of correct answers pre to post for either the question about engineers ($p = 0.250$, $n = 10$), or about scientists ($p = 1.000$, $n = 10$). For most questions about defining bioengineering, engineering, and science, the number of correct responses increased from pre to post. Interestingly, the number of responses that conflated or confused the three fields also increased pre to post, although not significantly so. This finding is understandable, given that the intervention was very brief and children were introduced to many novel concepts and vocabulary words

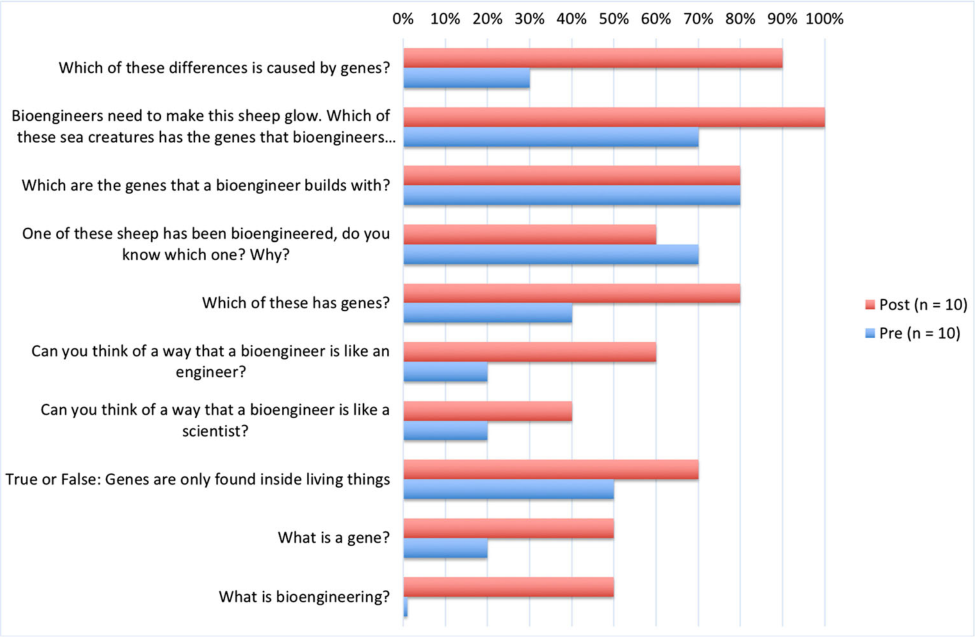


Fig. 11 Proportion of correct answers in Bioengineering Educational Assessment pre- and post-tests of bioengineering content knowledge (*n* = 10)

in a short time. Rather than problematizing these answers as "incorrect," this finding may suggest that children in our sample were reimagining the practices of these three fields as very interrelated.

Quantitative Trends Across both Implementations

N = 25 children from both implementations responded to the open-response items, "What is bioengineering?" and "What is a gene?" Researchers coded for the answer to the first question against this definition offered during the intervention: "bioengineering means building or changing living things/genes in order to solve problems." No child in either intervention correctly defined bioengineering in the pre-assessment, and 20% defined it correctly after the intervention. Some children attempted to interpret the unfamiliar word based on what they already knew about biology and engineering. For example, in pre-tests, one 7-year-old boy responded: "Bio means like

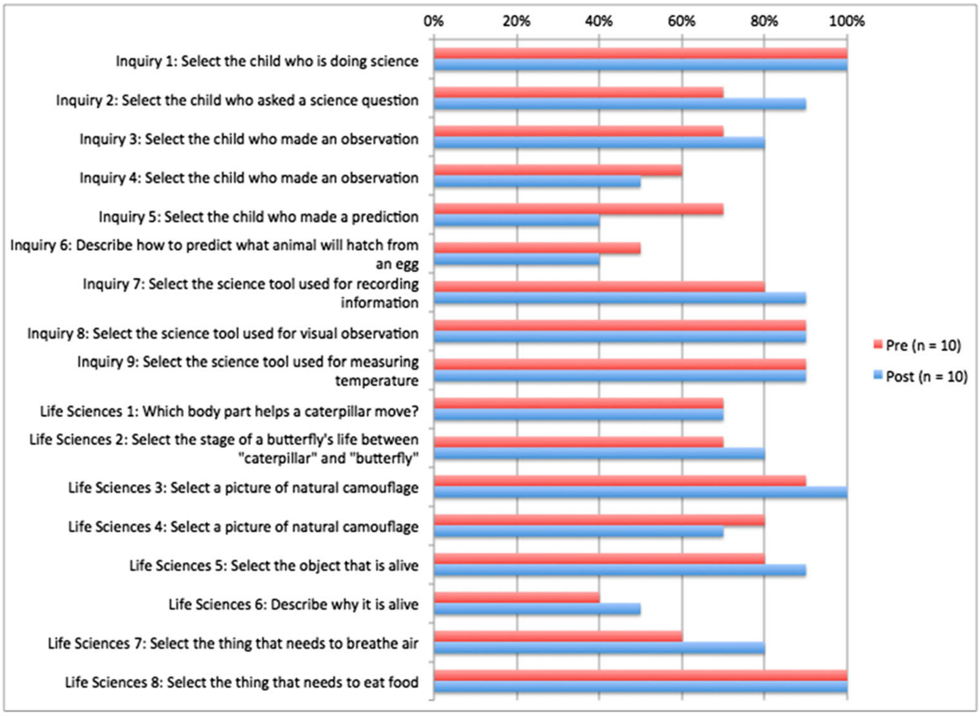


Fig. 12 Proportion of correct answers in Science Learning Assessment pre- and post-tests of science inquiry and content knowledge

nature, and engineering means something that helps that engineers make, so bioengineering is something that helps nature." Children's open-ended responses prior to the intervention reveal very few preconceptions about the term "bioengineering." In defining the term "gene," children showed more evidence of prior exposure. Raters compared responses to the following definition: "Genes are the building blocks of all living things and they contain many instructions. Living things look different because their genes are different." Although this was not directly addressed during the intervention, children had sufficient prior experience with the concept of genes to warrant this change to the scoring rubric. They also accepted references to genes being passed down from parents to offspring, and being like a "recipe." There were significantly more correct answers in post-tests ($p = 0.003$, $n = 21$), with 12% of children able to correctly define "gene" before the intervention, and 52% able to define it after. Children's pre-intervention responses reflected a diversity of prior experience with the concept of genes (see Table 5). Some children relied on prior experience with the homonym word "jeans" and referred to their pants. Other children connected to broad concepts of hygiene, referencing germs and bacteria. Children who mentioned germs associated genes with negative outcomes, such as making humans sick and dirty. Some children had no experience or took a guess, and still others had fairly well-developed theories about how genes alter a person's appearance, sometimes even referring to high school–level vocabulary such as "DNA" and "chromosome."

Children in both implementations also responded to the open-ended question: "What is engineering, or what do engineers do?" Raters' scores of children's responses showed no significant difference in the proportion of correct answers pre- and post-interventions. This is likely because nearly half of the sample ($n = 11$) correctly defined engineering as building or making things prior to the intervention. From this result, we can conclude that children in our sample were exposed to engineering outside of the study context. One child even responded that engineering is "a center" (i.e., a classroom activity center), suggesting the penetration of engineering education in formal learning settings. Despite the fact that many children associated engineering with building and that children generally agreed with the statement that "engineering is useful to helping solve problems," it is worth noting that very few children spontaneously described engineering as a way to help people or solve problems. In pre-assessments, no children mentioned helping behaviors as part of their definition of engineering, compared with only four children in post-tests. For example, a boy aged 7;3 said, "engineering is…when engineers build stuff to help something in a cause", and a boy aged 6;8 said, "[engineering is] things that people build to help." This finding has implications for children's ethical reasoning when engaged in engineering, and will be addressed in the discussion.

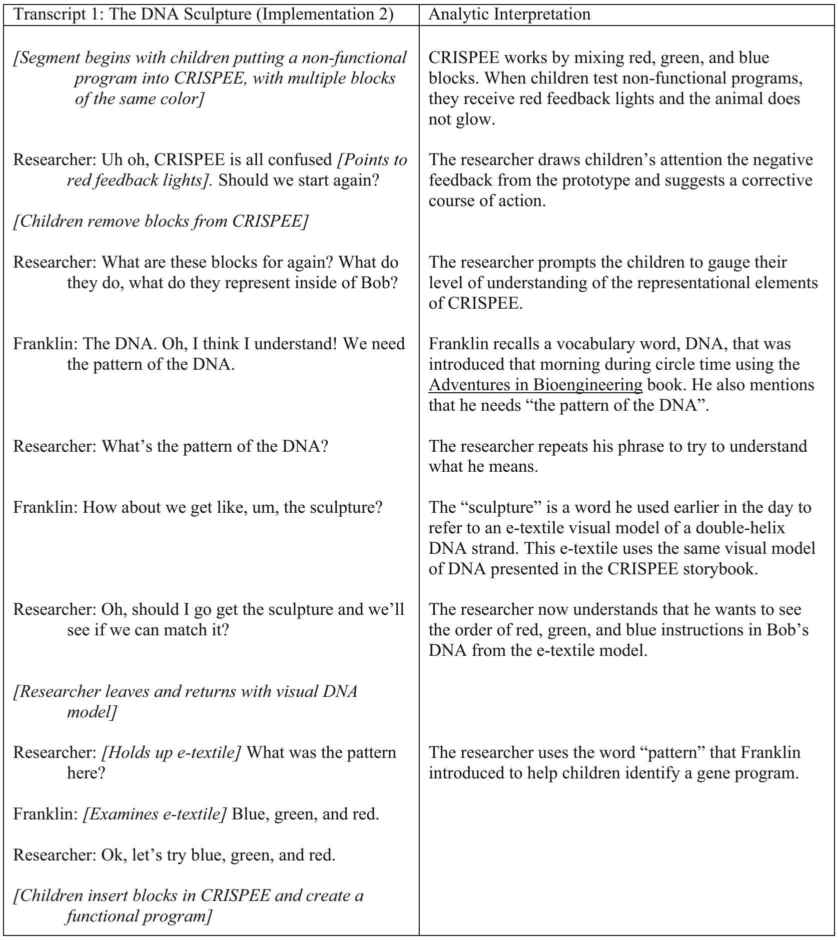
Qualitative Findings

The primary finding from the quantitative assessments is that after the workshops, children showed incremental (non-significant) improvement in understanding bioengineering as a domain, and children in both implementations significantly improved in their ability to define and explain "genes" or "DNA" (used interchangeably in both sessions). To further understand this phenomenon, we looked closely at instances when children used the words genes or DNA on their own, or proposed their own bioengineering designs (e.g., a plan of how to change an animal's light), which often happened when they were playing with the CRISPEE prototype. The following vignettes demonstrate these findings (see Fig. 13).

In this transcript, Franklin (6;5) had an idea to make his program like the pattern of the DNA in the "sculpture." Based on an earlier conversation, the researcher understood that the sculpture he referred to was an e-textile, made of LED-enabled felt and conductive embroidery thread, that depicted a visual model of a DNA double-helix strand with glowing red, green, and blue "ladder-rungs" to model how DNA contains instructional information about red, green, and blue

Table 5 Sample of children's pre/post responses to the question: "What is a gene?"

Implementation	Gender	Age	Pre	Post
2	M	4;11	Pants.	It's pants.
2	M	5;1	I do not know. People and things that are living have them.	Something that makes you look taller.
1	F	5;5	I do not know	A building block of any living thing
2	M	6;5	How your parents are, like how big you are even if somebody's older than you. Everyone has DNA in their body.	How your parents are and how you are. Genes are inside of living things.
1	M	7;3	Probably like DNA, like the building blocks of life sort of thing	*No response. Participant was absent on day of testing.*
2	F	7;8	Something you get, like a gene like from your mom or dad or something. Something you get from your mom and dad that makes you the same.	A gene is a part of your body that makes you look different and unique and sometimes it makes you look the same.



Transcript 1: The DNA Sculpture (Implementation 2)	Analytic Interpretation
[Segment begins with children putting a non-functional program into CRISPEE, with multiple blocks of the same color]	CRISPEE works by mixing red, green, and blue blocks. When children test non-functional programs, they receive red feedback lights and the animal does not glow.
Researcher: Uh oh, CRISPEE is all confused *[Points to red feedback lights]*. Should we start again?	The researcher draws children's attention the negative feedback from the prototype and suggests a corrective course of action.
[Children remove blocks from CRISPEE]	
Researcher: What are these blocks for again? What do they do, what do they represent inside of Bob?	The researcher prompts the children to gauge their level of understanding of the representational elements of CRISPEE.
Franklin: The DNA. Oh, I think I understand! We need the pattern of the DNA.	Franklin recalls a vocabulary word, DNA, that was introduced that morning during circle time using the Adventures in Bioengineering book. He also mentions that he needs "the pattern of the DNA".
Researcher: What's the pattern of the DNA?	The researcher repeats his phrase to try to understand what he means.
Franklin: How about we get like, um, the sculpture?	The "sculpture" is a word he used earlier in the day to refer to an e-textile visual model of a double-helix DNA strand. This e-textile uses the same visual model of DNA presented in the CRISPEE storybook.
Researcher: Oh, should I go get the sculpture and we'll see if we can match it?	The researcher now understands that he wants to see the order of red, green, and blue instructions in Bob's DNA from the e-textile model.
[Researcher leaves and returns with visual DNA model]	
Researcher: *[Holds up e-textile]* What was the pattern here?	The researcher uses the word "pattern" that Franklin introduced to help children identify a gene program.
Franklin: *[Examines e-textile]* Blue, green, and red.	
Researcher: Ok, let's try blue, green, and red.	
[Children insert blocks in CRISPEE and create a functional program]	

Fig. 13 Transcript from a CRISPEE play session in which children use visual models of DNA to plan their CRISPEE program

bioluminescence (see Fig. 14). This visual model was presented in the workshop during a reading of the *Adventures in Bioengineering* storybook, which also depicted the same visual model (see Fig. 15). When the researcher brought the e-textile in to show Franklin, he copied the order of the colors in the image into his CRISPEE program. From this example, we can deduce that Franklin was using CRISPEE to model DNA, by relating the blocks to the information contained in genetic DNA strands. It is unlikely that he made this connection without the mental model of genetic instructions because aside from colors, the e-textile sculpture and the CRISPEE blocks are morphologically quite different.

In this next transcript, Ivan (7;2), Veronica (7;8), and Alisha (7;10) were trying to see how many different lights they could create with CRISPEE programs (see Fig. 16).

While working with CRISPEE, several children referenced characters and images from the original storybook. In this transcript, we see that Alisha used her experience with the CRISPEE storybook to help work through a technical challenge (see Fig. 17). Specifically, she understood the difficult concept of "light off" blocks by relating back to the *Adventures in Bioengineering* storybook that children heard that morning. She simultaneously made two mental moves to navigate her challenge. First, she associated the picture of the firefly on the faceplate with the picture of Bob the firefly from the story, calling the CRISPEE faceplate "Bob". She recalled that in the story, Bob was introduced as a non-glowing firefly (see Fig. 18). Second, she assigned an emotional motivation to Bob—he wants to be like his friends—that justified her next suggestion, to change the "off" light to a pink light. Similar to Franklin's use of visual models of DNA to understand the mechanism of a CRISPEE program, Alisha used the plot and characters of the storybook to orient her bioengineering design process.

Additionally, the assessments in implementation 2 suggested that children began to conflate elements of engineering and bioengineering. One possible explanation for this finding is that children modeled bioengineering with CRISPEE while simultaneously exploring the CRISPEE prototype itself. Several children were curious about the interior circuitry of CRISPEE, about who built it, and what the wires did (see Fig. 19). When asked what would happen if the wires were removed, children said things like, "then it won't work" (Alisha, age 7;10) and "it will just be a toy" (Adam, age 6;2). When told that the researchers had helped to develop CRISPEE, they asked specific details about what tools we

Fig. 14 This image shows Franklin (foreground) looking at the "sculpture" he requested. The sculpture was an e-textile, made of LED-enabled felt and conductive embroidery thread, that depicted a visual model of a DNA double-helix strand. The bars in the double helix glowed in green, blue, and red light to model how genes contain information for the light color of bioluminescent animals

used and whether we used our own hands. They could also have become confused about what engineering is because researchers introduced themselves as scientists hoping to learn about the children's ideas during pre-/post-testing, but also demonstrated that they were engineers of CRISPEE. All of these factors could have contributed to the conflation of engineering, science, and bioengineering that children demonstrated at the end of the implementation 2 workshop.

Finally, many children demonstrated preconceptions about science and engineering before the intervention, and in implementation 2, some children showed prior experience with bioengineering-relevant concepts of genes and the inheritance of biological traits. In order to explore the unexpectedly high proportion of correct pre-test answers, researchers followed up with certain parents of high-scoring participants. Findings varied, but a common theme emerged that idiosyncratic experiences outside of the intervention contributed to prior knowledge. For example, the mother of a 7-year-old girl from implementation 2 explained her daughter's prior experience with genes: "my daughter is quite small for her age, and she began to ask us [her parents] why she didn't look like other children in her classroom. We've had a lot of conversations at home about how everyone looks a little like other people in their family, because they all share genetic instructions with each other. My daughter knows that she shares my husband's and my genes for being short" (personal communication, April 20, 2018). Other discussions revealed that some children had family members who worked in biomedical fields, or simply had an affinity for life science.

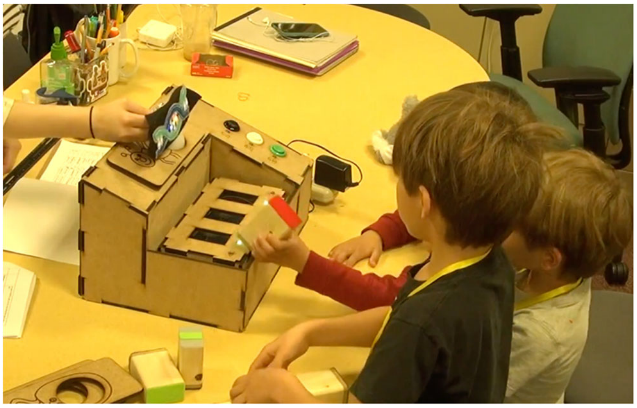


Fig. 15 A child uses an e-textile model of a DNA double-helix (what he calls a "sculpture") to build his CRISPEE program

Discussion

The aim of the present study was to explore children's bioengineering attitudes and content knowledge before, during, and after an experimental pilot learning intervention with the CRISPEE technology and curriculum. We identified two hypotheses earlier in this article about what would happen to children after a CRISPEE intervention. First, we predicted that children would show increased positive attitudes toward bioengineering, engineering, and life science. Second, we further predicted that children would show increased understanding of concepts from all three of these domains. We further posited that, based on prior research with older children, presenting bioengineering as a creative design activity rather than a science observation activity would deepen children's engagement with bioengineering concepts (Kafai et al. 2017; Kuldell 2007); that the tangible CRISPEE technology would allow children to leverage their intuitive knowledge about the physical world during their design play (Bers 2018; Papert 1980; Wilensky and Resnick 1999); and that a story-based context would engage children in the "helping" or ethical problem-solving applications of biodesign (Burke 2007; Drechsel et al. 2011; Miller et al. 2006).

The results drawn from quantitative assessments and qualitative vignettes suggest that the CRISPEE bioengineering intervention had a positive impact on children's STEM attitudes. Specifically, children in our sample began the study with neutral to positive opinions about science, engineering, and bioengineering, and either maintained or improved those opinions after the intervention. In pre-tests, children demonstrated preconceptions about science and engineering, as well as some foundational bioengineering concepts, particularly genes and the inheritance of biological traits. Thus, we confirmed our hypothesis that children would show slightly higher positive attitudes toward the three STEM domains after the intervention, but more work is needed to understand the nature of children's high positive affinity at baseline, and

Fig. 16 Transcript from a CRISPEE play session in which children use the *Adventures in Bioengineering* storybook to plan their CRISPEE designs

Transcript 2: Bob Wants To Be Like His Friends (Implementation 2)	Analytic Interpretation
[Segment begins with children looking a completed "light off" program]	The children have created a program with all short striped blocks, which turns all colors off.
Researcher: So, it worked! These lights are telling us it worked *[Points to white feedback lights]*. But what color did we make with only short ones? *[points to blocks inside of CRISPEE]*	The researcher draws children's attention the positive feedback lights on CRISPEE, despite the non-glowing animal light bulb.
Ivan, Veronica, and Alisha: White	Many children are confused or disappointed the first time they see an off program, and assume that because it is functional, there must be a light color.
Researcher: Is that the same as white? *[Points to lightbulb inside of firefly faceplate]*	The researcher invites them to use observations to justify their ideas. They have already made a white light in this play session.
Veronica: *[frowning]* Clear.	Veronica acknowledges that this looks different from white, but still seems confused.
Researcher: Clear. It's kind of off, isn't it?	The researcher acknowledges the word clear and offers "off"
Alisha: *[frowning]* Yeah.	
Researcher: This isn't lighting anything up *[points to lightbulb]*. So what do these short ones *[points to CRISPEE off blocks]* make the program do?	Researcher prompts to help children understand the concept of blocks that code for a *lack* of color
Veronica: Nothing.	Veronica demonstrates that she understands the concept of an "off" block
Alisha: Maybe we need Bob…Bob wants to be like his friends so maybe we should make him just light up.	Alisha refers to the faceplate that looks like Bob the firefly from the Adventures in Bioengineering storybook. She also recalls a plot point from the story, that Bob chose to be bioengineered to glow like his friends.
Researcher: Just light up? Do you remember what color his friends were?	The researcher plays along and asks about details from the storybook.
Veronica and Alisha: Pink	
Alisha: So we need a program to make it pink. *[Children try to program a pink light]*	This storybook conversation has inspired the next round of bioengineering design.

which specific elements of the intervention might have contributed to any increased attitude scores.

There are four core findings of this study, which are related to children's learning after the CRISPEE workshop intervention. First, bioengineering/biology knowledge was the main content knowledge area where children showed significant improvement, suggesting that content knowledge does not generalize as broadly across the three domains of interest. By implementation 2 post-tests, more than half of the sample were able to correctly define genes and to describe the function of genes in living beings after the intervention. Second, children began to describe engineering, science, and bioengineering as interrelated fields, with shared goals of generating knowledge in order to design and build problem-solving solutions. We attribute this finding to children's experience of the tangible CRISPEE kit, which sparked concurrent conversations about engineering concepts (e.g., wires, electricity, prototyping), microbiology (e.g., blocks as gene instructions and DNA models), and bioengineering design (e.g., planning and implementing specific colors for animals referenced in a picture book). Third, children began to explicitly identify the goals of engineering and bioengineering work as "helping," "fixing," or "solving problems" for people, animals, or the environment. This suggests that our use of story contexts did help to engage children in prosocial applications of bioengineering designs. Further, our framing of

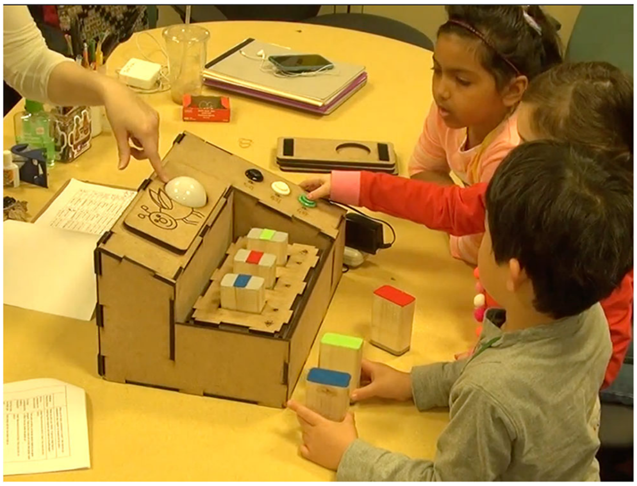
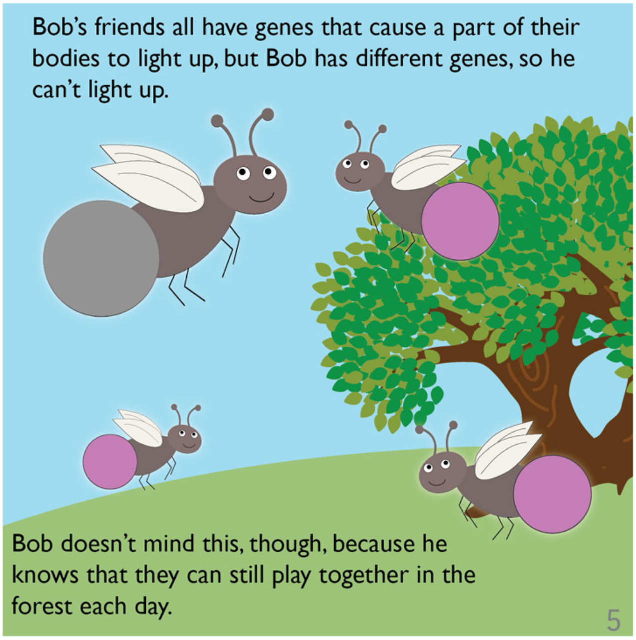


Fig. 17 Children learned that using all short, striped "color off" blocks resulted in a non-glowing animal



Bob's friends all have genes that cause a part of their bodies to light up, but Bob has different genes, so he can't light up.

Bob doesn't mind this, though, because he knows that they can still play together in the forest each day.

5

Fig. 18 This page from the *Adventures in Bioengineering* storybook depicts the main character, Bob, with a non-glowing gray body, and his friends, who all glow pink

bioengineering as a creative design activity allowed children to generalize the goal-directed, ethical applications of bioengineering to the field of engineering. Fourth, a handful of children in post- (but not pre-) assessment interview asked questions about the purpose and justification (the "why") of bioengineering work. Children's curiosity suggests they were thinking about ethical impact and trying to identify a helpful purpose behind decontextualized bioengineering examples. By inquiring into bioengineers' motivations for their designs, these children were effectively asking "what problem are they trying to solve?" The bioengineering curriculum and storybook offered children a developmentally appropriate context within which to situate bioengineering activity, and therefore offered children with little-to-no prior bioengineering exposure to engage richly in biodesign and critical evaluation of bioengineering work.

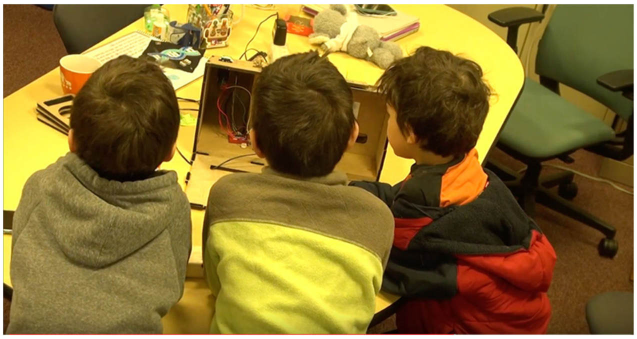


Fig. 19 Three boys examine the interior wiring of the CRISPEE prototype

In sum, the majority of children in our sample showed positive STEM attitudes upon completion of the intervention, and demonstrated preliminary learning about core concepts in foundational bioengineering, such as the definition of genes. Several children engaged in bioengineering as a self-directed design activity, and expressed the view that bioengineering has helpful applications for solving environmental, animal, or human problems. A few children demonstrated an ability to reason why bioengineers might make certain design choices, and to describe their own criteria for making such decisions. The results from this experimental pilot 3-day intervention support the hypothesis that novel STEM concepts may be absent from young children's education settings for reasons more related to a lack of learning resources than to children's developmental constraints (Davis 2003; Metz 2011; Trundle and Saçkes 2015). Next, we discuss the implications of these results for designers of educational technologies and curricula, and explore options for expanding the current study to further investigate bioengineering education for young children.

Implications and Future Work

As one of the first studies to explore a bioengineering curriculum for 4–7-year-old children, the results presented here offer implications for future work in this area. The finding that children in our sample already held some preconceptions about genetics and engineering design is of pivotal importance to imagining a bioengineering curriculum in early childhood. Children's idiosyncratic experiences provide a foundation for rich engagement when the same concepts are encountered again in learning settings (Falk and Adelman 2003; Schmidt et al. 2015). One area of bioengineering education research that requires further research is better understanding children's prior exposure to relevant concepts. Where does the exposure come from? What are trends in children's preconceptions, and are they similar to adult preconceptions? As part of our iterative design process, our research team is already investigating ways to understand children's intuitive bioengineering ideas.

Another key finding is that, as in studies with older children (e.g., Kafai et al. 2017; Kuldell 2007; Loparev et al. 2017; Okerlund et al. 2016; Strawhacker et al. 2018; Walker et al. 2018), young children are able to engage in bioengineering as a creative, design-oriented domain similar to engineering when technological tools invite them into a constructionist-oriented exploration of biodesign. Further, increased bioengineering knowledge did not necessarily correlate with increased engineering or life science knowledge. This suggests that bioengineering is distinct from more established science and engineering fields, and deserves investigation as a separate but related domain in the early childhood curriculum. By offering developmentally appropriate learning technologies and settings, placing children in the role of a bioengineer, and providing a story-based context with a specific problem to solve, children reached a level of basic understanding about bioengineering relatively quickly and showed high levels of enjoyment and engagement. The CRISPEE tool facilitated this learning through a screen-free, tangible platform made of age-appropriate materials built to resemble existing equipment found in bioengineering labs. Providing an approachable and playful tool that encourages free exploration and repetition through physical actions aided in solidifying their self-identification with and interest in bioengineering concepts and methods. Educators can use tools like these to support early access to ideas of bioengineering that already permeate children's lives outside of school, and introduce children to tools and methods used in scientific environments.

Finally, after a brief intervention, a few children were able to begin asking high-level questions about the purpose and consequences of bioengineering work. In future work, the research team will make the evaluation of tradeoffs and consequences an explicit learning goal of the CRISPEE curriculum. As prior research shows, bringing an ethical dimension into bioengineering education is challenging at the secondary and college levels (Balmer and Bulpin 2013). This study adds to the literature by arguing that early childhood, a time when learners are focusing on collaboration, consequences for actions, and interpersonal skills, may be an opportune time to engage children in bioengineering work (Balmer and Bulpin 2013; Bers 2018). Early intervention may encourage children to view inquiry and design in bioengineering as subject to human error, another challenge facing engineering and science education (Chang 2005).

Limitations

This exploratory study has a number of limitations. First, this study highlights a need to better understand where children's preconceptions about genes come from. Conversations with families informally suggest prior experience, but more work is needed to unearth the types, settings, and contexts of those experiences that can prepare a child to think about foundational bioengineering topics. Another limitation of the study is the small sample size. In the future, larger studies with more diverse samples of children are needed to investigate children's attitudes and knowledge before and after bioengineering learning interventions. Such studies can provide better understanding of how to support children's learning in bioengineering, in particular children with different levels of STEM exposure. Finally, we acknowledge that the design of the intervention and the teaching materials are necessarily rooted in the perspective of the research team. While our collaborative interdisciplinary team comprises designers, technologists, bioengineers, and developmentalists, bioengineering is a sensitive and poorly understood domain of education, even at the pre-professional level. This limitation represents an opportunity for the research community to consider the societal dimensions of bioengineering and agree upon ways to integrate it as a social, civic, ethical, and intellectually honest learning domain for the future citizens of our world.

Conclusion

This study presents an argument for exploring a twenty-first century bioengineering curriculum for young children (ages 5–8 years), supported by results from a pilot bioengineering learning intervention using the tangible CRISPEE technology. Our findings indicate that children in our sample engaged in practices and skills relevant to STEM, including science inquiry and engineering design. In response to our research questions about children's initial attitudes, inquiry approaches, and content knowledge related to bioengineering, we have found that children do indeed harbor complex early conceptions about genes and gene editing. After a CRISPEE learning intervention, children showed an ability to retain conceptual knowledge about foundational bioengineering concepts, as well as engage in science inquiry about the purpose of bioengineering activities. The CRISPEE technology and storybook emerged in children's play activities as useful contexts for situating the work of a bioengineer, and several new directions were identified for the future development of these intervention tools.

We look forward to expanding this research by further investigating CRISPEE and other learning interventions as pathways for children to explore foundational bioengineering, thus shedding light on the theoretical, developmental, and educational dimensions of introducing young children to emerging interdisciplinary STEM domains.

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Compliance with Ethical Standards

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