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ENHANCING CHILDREN'S INTEREST AND KNOWLEDGE IN BIOENGINEERING THROUGH AN INTERACTIVE VIDEOGAME

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ABSTRACT

Aim/Purpose	Bioengineering is a burgeoning interdisciplinary learning domain that could inspire the imaginations of elementary aged children but is not traditionally taught to this age group for reasons unrelated to student ability. This pilot study presents the BacToMars videogame and accompanying curricular intervention, designed to introduce children (aged 7-11) to foundational concepts of bioengineering and to the interdisciplinary nature of scientific endeavors.
Background	This pilot study explores the bioengineering-related learning outcomes and attitudes of children after engaging with the BacToMars game and curriculum intervention.
Methodology	This study drew on prior findings in game-based learning and applied them to a videogame designed to connect microbiology with Constructionist microworlds. An experimental comparison showed the learning and engagement affordances of integrating this videogame into a mixed-media bioengineering curriculum. Elementary-aged children (*N* = 17) participated in a 9-hour learning intervention, with one group of *n* = 8 children receiving the BacToMars videogame and the other group (*n* = 9) receiving traditional learning activities on the same content. Pre- and post-surveys and interview data were collected from both groups.

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Contribution	This paper contributes to education research on children's ability to meaningfully engage with abstract concepts at the intersection of science and engineering through bioengineering education, and to design research on developing educational technology for introducing bioengineering content to elementary school children.
Findings	Children in both groups showed improved knowledge and attitudes related to bioengineering. Children who used BacToMars showed slightly stronger performance on game-specific concepts, while children in the control condition showed slightly higher generalized knowledge of bioengineering concepts.
Recommendations for Practitioners	Practitioners should consider bioengineering as a domain for meaningful, interdisciplinary learning in elementary education.
Recommendation for Researchers	Design researchers should develop playful ways to introduce bioengineering concepts accurately and to engage children's imaginations and problem-solving skills. Education researchers should further investigate developmentally appropriate ways to introduce bioengineering in elementary education.
Impact on Society	BacToMars introduces a meaningful scenario to contextualize complex concepts at the intersection of science and engineering, and to engage children in real-world, interdisciplinary problem solving.
Future Research	Future research should explore BacToMars and bioengineering curricula for elementary-aged children in larger samples, with longer intervention times.

Keywords: biological engineering, elementary school, videogames

INTRODUCTION

The fields of biology and engineering have become a driving force in today's world, inspiring innovation in medicine, agriculture, energy, and space travel. The intersection of these two fields, known as *bioengineering*, is a unique interdisciplinary domain that is motivated by the novel ways it combines science and technology to address critical real-world problems. For example, bioengineers may create innovative medical devices, design new pharmaceutical drugs, or even develop environment-friendly fuels and power sources.

Despite the widespread impact of bioengineering in the United States, a typical elementary natural science curriculum does not include emerging domains of knowledge like bioengineering that cut across disciplinary boundaries (National Research Council, 2007; Rampey, Dion, & Donahue, 2009). There are many potential reasons for not including biological engineering in the current elementary school curriculum, including uncertainty about students' ability to understand bioengineering concepts. However, recent research has shown that children are able to master foundational concepts of emerging science, engineering, and technology concepts much earlier than previously believed (Bers, 2018; Greenfield, 2015). This suggests that, in practice, children might not be currently exploring bioengineering because of challenges in implementation, such as teacher attitudes and preparedness and a lack of consensus about the best practices for introducing bioengineering in early elementary (Johnson, Peters-Burton, & Moore, 2015; Kafai et al., 2017; Stieler-Hunt & Jones, 2015). This is a missed opportunity, as the exciting and unanswered questions at the center of real-world bioengineering represent a rich way to engage elementary students in STEAM (Science, Technology, Engineering, Liberal Arts and Mathematics) explorations that tap into existing foundational disciplinary standards for their age range. Curricular interventions in 21st century domains may be especially beneficial to minorities and girls, who are underrepresented in STEAM fields as adults due in part to long-standing bias in more established disciplines (Corbett & Hill, 2015).

Research on human-computer interaction over the past two decades has shown that new technologies can be used to foster a developmentally appropriate and playful introduction to science and engineering, beginning in the early childhood years (Bers, 2018; Okerlund et al., 2016; Strawhacker & Bers, 2015; Sullivan, Strawhacker, & Bers, 2017). Pioneering work on bringing bioengineering into K-12 classrooms, such as Kafai et al.'s (2017) biomakerlab interventions and Kuldell, Bernstein, Ingram, and Hart's (2015) BioBuilder curriculum resources have shown early promise for bioengineering education in high school settings. Additionally, recent research initiatives about game-based learning by groups such as the Digital Games Research Association (http://www.digra.org/) and the Serious Games Network (http://seriousgamesnet.eu/) have demonstrated the benefits of videogames for engaging children and youth in rich, novel classroom learning experiences (de Freitas, 2006a, 2006b). Prior research has explored best teaching practices for integrating science-themed videogames into learning settings (Sandford, Ulicsak, Facer, & Rudd, 2006; Stieler-Hunt & Jones, 2015), as well as identifying elementary students' attitudes regarding science-themed games (Kao, Galas, & Kafai, 2005). However, little research has been done to explore students' learning outcomes after a videogame-integrated curriculum, or to control for the videogame as a factor in these learning outcomes. The current study is designed to explore these questions and, thus, to contribute to the growing number of game-based tools and resources specifically focused on introducing *pre*-high school students to foundational concepts of bioengineering.

The BacToMars videogame (Loparev, Sullivan, et al., 2017), which we evaluate in this paper, allows users to take on the role of a scientist on a space mission to Mars. In the game, they must grow resources to survive out of genetic material from natural resources found on Mars and in their ship. The goal is to create a launch pad and build a rocket ship to return to Earth, while simultaneously creating enough water, food, and air to survive the harsh Martian environment. BacToMars was designed to inspire the next generation of innovators and scientists by exposing elementary-aged children to foundational bioengineering concepts and address the gap in educational bioengineering games for this age range. In addition to introducing children to concepts of science and technology, the game was also designed to foster the development of age-appropriate reading comprehension, mathematics skills, creative problem-solving, and collaboration.

The pilot-study presented here evaluates the impact of the BacToMars videogame on early elementary school children's attitudes and interest in science as well as their knowledge of foundational biological engineering concepts. Additionally, this pilot study also investigates how enjoyable the game experience was for participants.

In the following sections, we will briefly summarize relevant research on bioengineering and game-based learning in elementary education. Following this, we will describe the design elements and game-play of the BacToMars videogame in detail, as well as the method and structure of the experimental bioengineering curricular interventions. Results from the intervention will be outlined, focusing on children's learning and engagement outcomes, which will then be discussed and situated within existing research. Finally, limitations of the current study and recommendations for future work will be discussed and the paper will conclude with a reflection about the impact of this work for the field of bioengineering education and game-based learning in the elementary years.

LITERATURE REVIEW

In this research summary, we first define bioengineering and describe several real-world applications and challenges in that field. Then, we highlight the potential for bioengineering to emerge as a cross-cutting, 21st century educational domain for pre-high school education. We next turn to game-based learning as a promising medium to engage children in novel, abstract STEAM domains and summarize current research on best practices and design principles for implementing game-based curricula. Finally, we summarize existing digital games and prototypes to introduce pre-high school learners to bioengineering and discuss the theoretical underpinnings for pursuing this new kind of educational tool.

Bioengineering

Biological engineering is an emerging interdisciplinary STEAM (Science, Technology, Engineering, Arts and Mathematics) field that unites practices of engineering with materials and methods from biology to solve real-world challenges (Weiss, 2001). Specifically, bioengineering draws upon the engineering principles of modularity (the idea that processes or systems can be subdivided into discrete components), standardization (the process of conforming objects or processes to measurable standards), and abstraction (the idea that implementation details can be organized into a layered hierarchy so that engineers can focus on a design challenge in one layer while ignoring other layers). These principles are then applied to the design of living organisms with new characteristics (Endy, 2005). Biological engineers design new organisms (such as bacteria) in order to solve problems in areas such as medicine, energy, and agriculture (Keasling, 2006).

Since 2003, the International Genetically Engineered Machine (iGEM) Foundation (www.igem.org) has worked to standardize biological materials for biologically-designed solutions to pressing medical, environmental, or agricultural issues. Their Registry of Standard Biological Parts contains over 20,000 "BioBricks," discrete genetic parts that can be snipped and joined to create DNA sequences for novel organisms (Shetty, Endy, & Knight, 2008; Smolke, 2009). For example, synthetic biologists have used genetically engineered solutions to clean plastic pollution in oceans (Zewe, 2016), improve the nutritional value of staple crops (Planta, Xiang, Leustek, & Messing, 2017) and even to save a human infant from a life-threatening congenital disease (Reardon, 2015).

Another real-world challenge that bioengineers are currently exploring is the use of synthetic biology for sustaining extended space travel (Menezes, Cumbers, Hogan, & Arkin, 2014). Manned missions to Mars are inherently expensive and dangerous and critical resources may become less wasteful and even sustainable through new uses of synthetic biology (Menezes et al., 2014). Technologies are being explored to aid in generating food and fuel, managing water and gas systems, and even manufacturing equipment on Mars. This cutting-edge application of bioengineering is the inspiration for the BacToMars videogame described in this paper.

Bioengineering in Elementary School

The recent boom in educational technology has proven that even children as young as age 5-7 years can master foundational concepts of novel and emerging STEAM fields (Bers 2018; Clements & Samara, 2003). Research has shown that from both an economic and a developmental standpoint, educational interventions beginning in early childhood and the elementary school years are associated with lower costs and stronger, more durable effects than interventions that begin later in childhood (Reynolds, Temple, Robertson, & Mann, 2001). Additionally, we know that women and minorities are still underrepresented in many STEAM fields (Hill, Corbett, & St. Rose, 2010). Prior work demonstrates the importance of piquing the interest of girls and minorities during their formative early childhood years before stereotypes regarding these traditionally masculine fields are ingrained in later years (Metz, 2007; Steele, 1997; Sullivan & Bers, 2016). Therefore, it is critical to target interventions and design tools for engaging younger children in exploring STEAM concepts.

Currently, few resources refer to biological engineering as a curricular theme for students younger than high-school age (Johri & Olds, 2014; Linsenmeier, 2003). Natural sciences curricula in the US do not touch on microbiology until high school and synthetic biology is reserved for higher education (Next Generation Science Standards [NGSS], 2013; National Research Council, 2007). Despite this, bioengineering is a unique way to engage children in real-world challenges that require integrated learning across STEAM domains. Additionally, many of the powerful ideas of bioengineering are accessible for young children based on other concepts already taught in traditional elementary curricula. For example, according to the Next Generation Science Standards (a K–12 science content standards framework developed collaboratively by the National Research Council [NRC], the National Science Teachers Association [NSTA], the American Association for the Advancement of Science

[AAAS] in the US) (NGSS, 2013), 3rd graders in the US are expected to understand that living organisms like plants and animals inherit traits from their parents (Standard 3-LS3 Heredity: Inheritance and Variation of Traits), that these organisms have unique life cycles (Standard 3-LS1 From molecules to Organisms: Structures and Processes) and that engineers solve human problems by weighing the consequences of various solutions and choosing the best course of action (Standard 3-5-ETS1 Engineering Design). All of these concepts are foundational to the field of bioengineering (Kuldell et al., 2015).

More research is needed to understand elementary student's ability to meaningfully engage with foundational concepts specific to bioengineering. The current study aims to address this gap in the empirical research literature.

Game-based Learning

Game-based learning is an exciting education trend because games are now being designed and used to maximize learner engagement, motivation, and curiosity – areas that are lacking in traditional school structures in the US and abroad (Joan Ganz Cooney Center, 2016; Sandford et al., 2006). Researchers argue that problem solving in educational virtual environments is similar to applying the scientific method to a new challenge and that it requires creativity and imagination as well as concentration (de Freitas, 2006a; Hoffman, 2009). Key elements of effectively-designed learning games include a narrative story-line to engage players, customizable avatars to support immersion in the game, game realism, a sense of challenge, and exploratory play approaches that give players a sense of control (de Freitas, 2006a). The main challenge outlined in games-based learning research is a lack of understanding of best teaching practices and student learning outcomes for game-based curricular interventions (de Freitas, 2006a). The BacToMars videogame used in this study was designed with these elements in mind, including customizable avatars and a story-based game structure, and is intended to be collaborative, open-ended, and based on real-world scenarios.

Videogame-supported classroom education has emerged as a new way to engage learners in novel STEAM domains. Stieler-Hunt and Jones (2015) examined the practices of elementary educators who successfully used games to support classroom learning, including games related to life-sciences curricula. Effective teachers considered student motivations while playing a game and questioned how they could cultivate peer relationships and inspire out-of-game engagement with learning content. For example, researchers observed a classroom of Australian students (aged 11-12 years) whose teacher used a videogame about oceans to initiate a month-long investigation of aquatic habitats, marine cartography, and extension activities initiated by the students, such as paintings and group dances inspired by sea-creatures. Stieler-Hunt and Jones (2015) emphasized the importance of out-of-game curricular support, as well as carefully selecting games that provide collaborative, open-ended experiences that connect to real-world challenges. Kao et al. (2005) explored the difference between a multi-user and a single-user game-based learning environment to teach science concepts of epidemiology to sixth-grade students. They developed two similar virtual environments, one single-user (players could interact with computerized agents) and one multi-user (players could interact with other live players in the game). Sixth-graders explored the games and rated their experiences. Although children enjoyed both games, the single-player seemed more educational to them and the multi-player offered more opportunity for collaboration and a sense of belonging in a community. Additionally, this study confirmed prior findings that constructing a personalized avatar spurred deeper involvement in the virtual world (de Freitas, 2006a, 2006b; Kao et al., 2005).

These examples demonstrate the potential of collaborative videogames to support elementary students' engagement and learning. This study addresses de Freitas' (2006a) call to extend the empirical research on learning outcomes and best practices for game-based learning in a science-themed curricular intervention. Based on prior research, we incorporated collaborative multiplayer modes and rich out-of-game experiences to support learning with the BacToMars videogame. By comparing two identical learning interventions and experimentally manipulating which intervention included the videogame, we further explored the unique contribution of an educational videogame to support students' engagement and learning.

BIOENGINEERING TOOLS FOR CHILDREN

Several games exist to engage youth with biological engineering concepts, including Spore (www.spore.com), Hero.Coli (www.herocoli.com) and Nancrafter (Barone et al., 2015). However, few games offer opportunities for players to use bio-design in creative ways to address open-ended problems. Some museum exhibition including e.pixel (Tech Museum of Innovation, 2014) and TrapIt! (Lee et al., 2015), allow young participants to observe and interact with live bacterial cells. The biodesignstudio exhibit in the Tech Museum of Innovation introduces visitors to foundational concepts of biological engineering such as inherited traits, using biological parts to design biological concepts and methods for building biological systems (Tech Museum of Innovation, 2016). However, few exhibits allow children to engage with biological design in creative ways to solve problems. SynFlo (Okerlund et al., 2016) is a museum exhibit that allows visitors, including children, to engage in a simulation of a synthetic biology experiment in which bacterial cells are engineered to detect and report the presence of environmental toxins. BacPack (Loparev, Westendorf, et al., 2017) is a museum exhibit that engages visitors of all ages in the design of bacterial cells that could help astronauts to produce required products (e.g., oxygen, water, nutrients, biomass) from resources available on Mars (e.g., CO, soil, and "astronauts' poop"). Both SynFlo and BacPack utilize tangible interaction (Shaer & Hornecker, 2008) to attract visitors to collaborate in a playful bio-design activity.

These interactive museum installations inspired the development of the videogame BacToMars (Loparev, Sullivan, et al., 2017), which offers a novel and exciting storyline (humans living on Mars) to contextualize STEAM concepts and demonstrates a real-world application for the concepts and skills that players must learn. The choice to use a digital environment for this tool is rooted in theories of Constructionism (Papert, 1980). Papert (1980) used the term "microworlds" to describe a discrete environment where everything will conform to the rules a child sets. These worlds, he argued, are fertile ground for children to cultivate ideas, test hypotheses, and construct new artifacts based on that learning. BacToMars is a videogame designed by the authors to leverage the creative opportunities of a microworld, by combining the practices of engineering design to the construction of helpful living organisms. In this way, BacToMars creates a micro-biology-world, where users can construct knowledge about biological engineering (Papert, 1980). The goal of BacToMars is for players to help a team of astronaut scientists survive on Mars by engineering bacteria that consumes resources available on Mars (carbon dioxide, sunlight, soil, and poop) to produce necessities to survive, such as water, air, and food. The unique storyline of BacToMars allows children to see direct impacts of choices made in the microworld on the human scientists living on Mars, who need biologically-engineered bacteria that produce oxygen, nutrients, water, and materials. This allows children to explore challenges that scientists face in the real world and design solutions intended to help people and promote scientific endeavors such as space travel.

BACTOMARS VIDEOGAME

BACKGROUND

The BacToMars videogame was designed for this study by the Wellesley College Human Computer Interaction (HCI) Lab and the Tufts University DevTech Research Group (Loparev, Sullivan, et al., 2017). BacToMars is based the interactive museum exhibit BacPack that was designed by the Wellesley HCI Lab (Loparev, Westendorf, et al., 2017). Results from an evaluation of the exhibit in the museum showed that visitors (adults and children) collaboratively tinkered and experimented with the exhibit. Observations of visitor interactions and a series of debriefing questions revealed evidence of learning and inquiry. The BacPack exhibit provided an example of how digital interfaces can be used to promote collaborative, interactive learning about bioengineering.

BacToMars draws on the basic premise of the BacPack museum exhibit but offers prolonged interactions for an audience of elementary children (2nd through 5th grade) through a web-based platform that can be easily accessed with a computer or tablet. The choice to design for this population was because the evaluation of BacPack in the museum demonstrated that children within this age range were able to engage and enjoy the exhibit while learning bioengineering concepts (Loparev, Westendorf, et al., 2017). BacPack was designed to address the following learning goals: introducing the basic concepts of genetics, with a focus on what genes are; facilitating the design of genetic programs that include input and output and where output from one program could serve as input to a different program; introducing the foundations of biological engineering; using methods and following a concrete process to build things that solve real-world problems; demonstrating the principles of abstraction and modularity (genes with documented functionality are used as standard biological parts and are combined to create new biological systems); and engaging players in creative problem-solving of critical challenges related to survival on Mars (Loparev, Westendorf, et al., 2017).

BacToMars Gameplay

The goal of BacToMars is for players to help a team of astronauts scientists to survive on Mars. These astronauts traveled to Mars to conduct research on the planet, but a dust storm destroyed their spaceship and supplies so that they must rebuild their supplies from scratch. Players assume the role of a scientist and choose their character representation at the beginning of the game (see Figure 1). A female game character (a biological engineer astronaut named Pam) teaches the players how to help the astronauts by engineering bacteria that consumes resources available on Mars (carbon dioxide, sunlight, soil, and poop) to produce products needed by the astronauts (see Figure 2). Products include basic needs such as oxygen, water, and nutrients, as well as materials such as biomass and fuel and metal. Once the players help the astronauts to sustain their basic needs, they proceed to produce products that the astronauts need in order to build a rocket ship to return to earth. Players accomplish these goals through bio-design and bioengineering methods – they select modular BioBricks (i.e., genes) that tell bacteria how to use resources to make products, combine them into a genetic program, and insert the program into plasmids so that a colony of engineered bacteria grow and are released to the Martian environment.

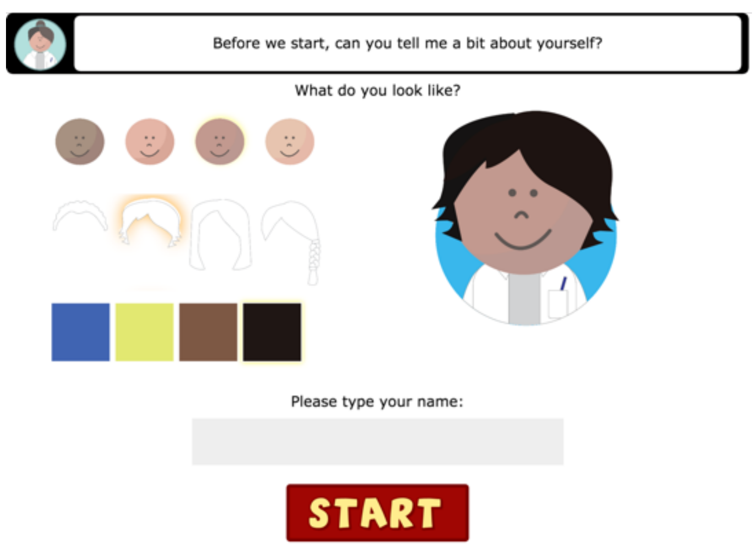

Figure 1: Character selection screen at the beginning of the game. Children choose their face, hair style and hair color and enter their name.

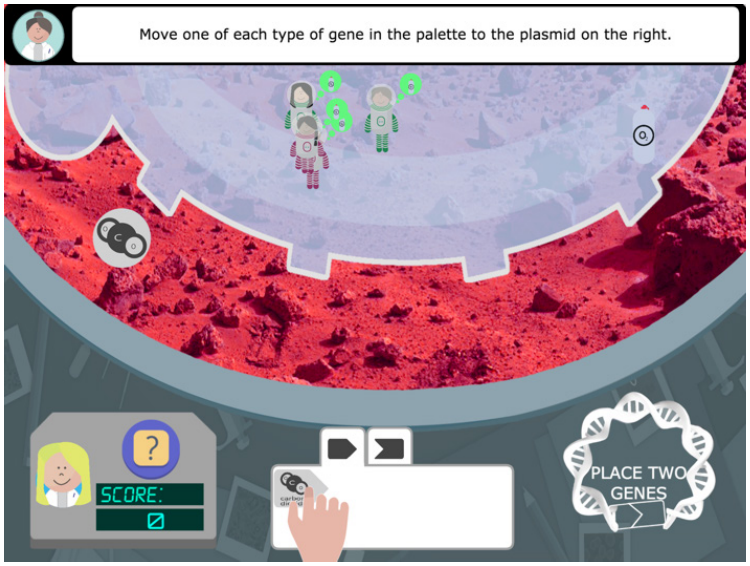

Figure 2: The first level of BacToMars, with on-screen scaffolding instructions to show players how to place genes.

In the game, players must discover which combinations of BioBricks yield the highest amount of product. Figure 2 depicts the BacToMars screen. The bottom of the screen shows the workbench with the player's character representation and score on the bottom right, the resource and product genes in the center, and the plasmid for their gene program on the right. The top half of the screen shows the biodome, where players see the team of astronauts and scientists, the output of their resource and product combination, and current levels of their products. Players can receive information from Pam by clicking on her character at the top of the screen. Players are then led through this process of discovery with a series of scaffolding levels that slowly introduce the resource and product BioBricks available to them. Figure 3 depicts all resource and product genes available in the game. Players start by creating oxygen, the most essential product for survival, and work their way through until they've also created water and nutrients. Players are then introduced to biomass, a product that can also be used as an efficient resource. Once players successfully create and use biomass, the collaborative element (multiplayer phase) of the game begins.

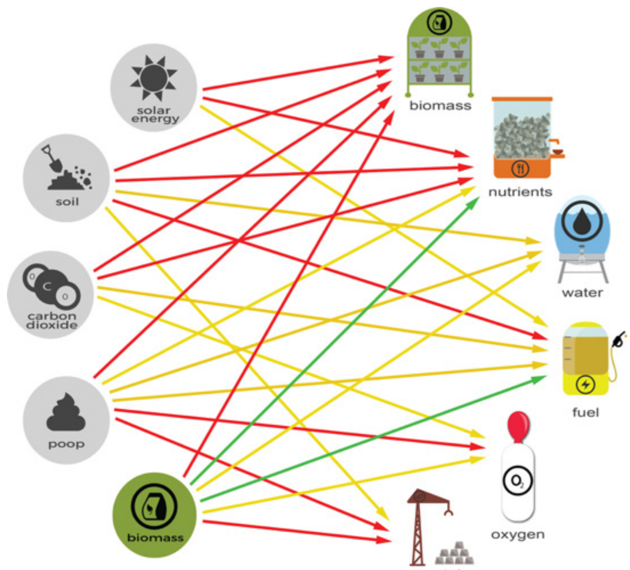

Figure 3: Resource and product combinations in the BacToMars videogame

Players work together to use metal and fuel, along with other products, to build their rocketship, as shown in Figure 4. In this level, players can use the natural resources on Mars to create metal and fuel, which the astronauts then use to build their rocket ship. Players can see what their team members are making by looking at the character representations along the edge of the workstation. Gameplay ends when the rocketship is complete and players receive feedback that outlines which resources and products they used and how that compared to the team (see Figure 5). During the game, players receive feedback on how well they combined BioBricks. Additionally, the astronauts tell the players what they need to create inside thought bubbles - these start out green, but if they are ignored they turn to yellow, then red, as time goes on (see Figure 2). After completing the entire game cycle, children should have a rich understanding about the challenges of space travel and the ways that bioengineering can aid astronauts.

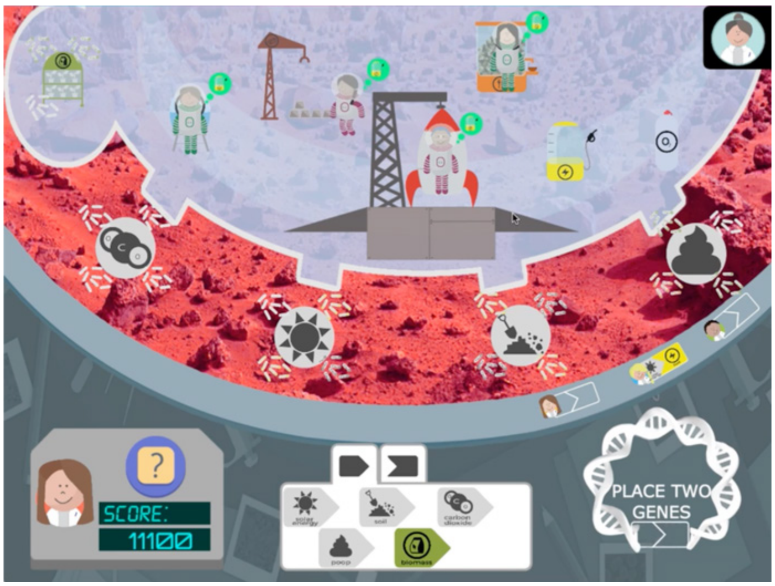

Figure 4: The final level of BacToMars.

Figure 5: The final screen of BacToMars, where players receive feedback on the resources and products they used and how that compares to their team.

BacToMars Implementation

The game is implemented as a multiplayer game in Javascript using the Phaser.IO game engine and is available online as a single-player game, together with all scaffolding material, videos and mini games, in the following url: http://cs.wellesley.edu/~bac2mars/games/BacPackTablet_multiplayer/public/

Although the game itself has many educational features, the context of gameplay is important for children's understanding of the learning content (Stieler-Hunt & Jones, 2015). Children in our study experienced the game as part of an intensive exploration of space travel and bioengineering which is described in the next section.

Methods

Inspired by successful game-based learning initiatives (e.g., those mentioned in Stieler-Hunt & Jones, 2015), we developed an experimental curriculum to accompany the BacToMars videogame, involving a range of media besides the videogame (e.g., minigames, videos, off-screen books, and games) to support learning. These curricular choices will be described in this section. In the current study, we explored the efficacy of this mixed-media, interactive curriculum to engage children in learning about bioengineering. In order to understand the unique learning affordances of the BacToMars game, a control curriculum was also developed that involved all of the same support technologies and activities, but excluded the videogame. Like Kao et al. (2005), we explored children's attitudes after single- vs multi-user play experiences about collaborative and individual play experiences. We also explored children's bioengineering learning outcomes to determine the educational effectiveness of the BacToMars game and curriculum. Based on prior research, we hypothesized that the videogame-enriched curriculum would show higher student satisfaction and similar learning outcomes to the non-videogame intervention.

Mixed method (qualitative and quantitative) data collection measures were employed in order to answer the following research questions:

1. How does the BacToMars videogame impact children's attitudes towards science?
2. How does the BacToMars videogame impact children's knowledge of foundational bioengineering content?

Children entering second through fifth grade were recruited to participate in a 3-day (3 hours each day, for a total of 9 hours) bioengineering-themed summer program held at Tufts University free of charge. Children were divided into 2 groups: Group 1 received a bioengineering curriculum that included the BacToMars videogame, and Group 2 (a control) received a nearly identical curriculum that did not include the BacToMars videogame. Children's attitudes and knowledge were assessed using pre and post surveys and interviews.

Sample

N = 17 children entering 2nd through 5th grade participated in the program. Based on the children's self-identification, there were *n* = 10 girls and *n* = 7 boys in this study (see Table 1 and Figures 6-7). Nearly all the participating children reported that they attend public schools in the greater Boston area, with *n*=15 children coming from public schools and *n* = 2 children coming from private schools.

Table 1: Participant demographics in each group

Group	Sample size	Grade	Gender
1 (Videogame)	8	63% 3rd 38% 4th	38% Male 63% Female
2 (Control)	9	45% 2nd 22% 3rd 11% 4th 22% 5th	44% Male 56% Female
Total	17	27% 2nd 47% 3rd 27% 4th 13% 5th	41% Male 59% Female

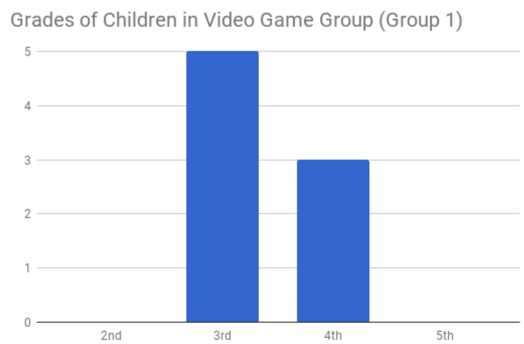

Figure 6. Grade distribution of children in the experimental condition (videogame group).

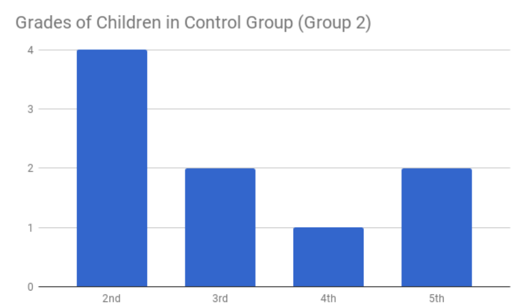

Figure 7. Grade distribution of children in control condition (non-videogame group)

Children were assigned to Group 1 (videogame intervention) or Group 2 (control) based on their availability and schedule. Group 1 had n = 8 children while Group 2 had n = 9 children.

INTERVENTIONS

All children in the sample engaged in a 9-hour bioengineering-themed intervention. Before and after the intervention, children's knowledge and attitudes about bioengineering were assessed. In order to identify the effect of the BacToMars videogame, children were assigned to either an experimental group (Group 1) or control group (Group 2) and engaged in a very similar learning intervention in both settings. Both groups explored off-screen games, stories and group activities as well as educational videos about bioengineering and "mini-games" designed for this study. However, only Group 1 played with the BacToMars videogame, an educational technology videogame designed to teach bioengineering concepts. Following, we describe the interventions and assessment instrument.

Both conditions: Traditional and technological learning activities

In both groups, daily activities were structured around a lesson theme related to foundational bioengineering concepts (see Tables 2 and 3 below). These topics included natural resources on both Earth and Mars, DNA and how engineers can reprogram it, and the types of genetic materials (i.e., "product genes" and "resource genes") that bioengineers can use when creating new biological solutions. Both groups explored the same concepts in the same relative order. Activities consisted of a mix of open-ended activities, such as free-building a construction using LEGO bricks; semi-structured activities, like a trivia game about natural resources; and guided activities, such as reading from an informational picture book about microbiology (see Figures 8-10). Children played trivia games to practice relevant vocabulary, such as "bioengineering," "engineering," and "microbiology," and explored tools of real microbiologists, such as microscopes, pipettes and petri dishes.

Figure 8. Children played trivia games about bioengineering.

Figure 9. Children used free-play time to create models of the surface of Mars using tablet software.

Figure 10. Children created models of the surface of Mars using LEGO and craft materials.

Additionally, children in both groups became familiarized with the images and vocabulary in the of the BacToMars game through a series of instructional videos and mini-games. These were designed to introduce children to the story behind the game and to provide background on concepts related to Mars, the environment, natural resources, bioengineering, and genetics. The animated videos were broken up into three 3-5 minute sessions to provide manageable amounts of information and were narrated by the lead bioengineer game character, Pam. The two minigames came after the first and third videos; the first minigame asked children to point to the natural resources on Earth and Mars (see Figure 11) and the second involved creating gene combinations to generate a specified product (see Figure 12). These minigames were developed in order to reinforce the most important ideas needed during gameplay, such as natural resources available on different planets. Researchers chose to include this experience in both weeks because the videos and minigames did not depend on the gameplay, and they thoughtfully explained the concepts explored earlier in the lessons in more depth.

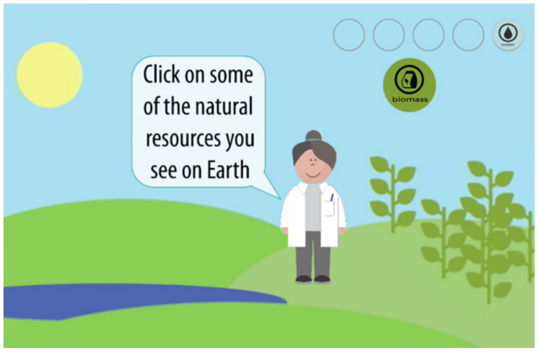

Figure 11. The first minigame, where players select natural resources on Earth and Mars.

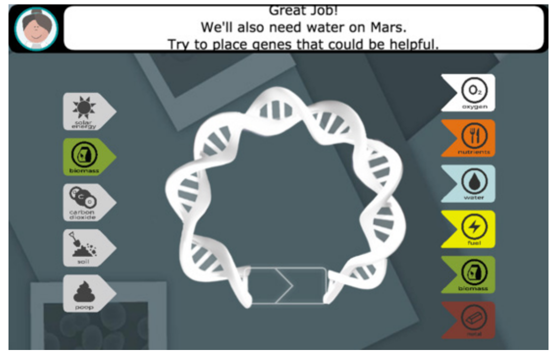

Figure 12. The second minigame, where players are asked to create a gene combination that will produce water.

Experimental condition: Playing the BacToMars videogame

The 3-day bioengineering intervention for Group 1 (*n* = 8 children) included off-screen games, tangible activities, the BacToMars educational videos and mini-games, and the full BacToMars videogame (see Table 2). The sessions lasted for 3 hours each day, for a total of 9 hours over the course of the 3-day intervention.

Table 2: Intervention Structure for Group 1 (experimental videogame condition).
Note. Activities in bold indicate activities that only the Group 1 condition engaged in.

DAY OF INTERVENTION	BIOLOGICAL ENGINEERING TOPIC	ACTIVITIES
Day 1 (3 hrs)	What are Natural Resources? What resources are found on Earth and Mars? What is the Environment of Earth and Mars?	Pre-surveys and interviews Engineering building activity using LEGO bricks Vocabulary Discussion: Biology, Engineering, Microbiology Trivia game about environmental resources Read from a children's picture book about microbiology
Day 2 (3 hrs)	What is DNA? How do engineers work with DNA on Earth and on Mars?	Videos and mini-games Debrief about content from videos and mini-games **Single-Player BacToMars videogame** Discussion about DNA and how engineers work with living materials
Day 3 (3 hrs)	What are "product genes" and "resource genes"? What is Microbiology?	**Multi-player BacToMars videogame** Explore tools of microbiology (e.g. microscope, droppers, petri dishes) Post-Surveys and Interviews

During the three BacToMars videogame sessions, a researcher worked directly with the children, observing and giving supportive prompts when necessary. For the single-player game, children were instructed to choose their character representation and to play the game from the beginning by following the scaffolding prompts. These children played until they reached the end of the game. For the multi-player game, children were broken up into groups of 3-4 and were seated at adjacent computers. They were told that this version of the game would be collaborative, but they were not told when the multi-player portion would begin. Each group played until they collectively finished the game.

Control condition: Student-led discussions and physical games

Children in the control group engaged in the same lesson plan, but did not explore the videogame. Instead of these activities, researchers planned comparable activities during the same timeslots. On day 2, instead of playing the single-player version of the videogame, children listened while researchers read aloud from a picture book about DNA and genetics. On day 3, instead of playing the multi-player version of the videogame, children played a physical collaborative game that involved printed images taken directly from the videogame to reinforce the concept of using "resource genes" to create "product genes."

The 3-day bioengineering intervention for Group 2 (*n* = 9 children) included many of the same off-screen games, tangible activities, BacToMars educational videos, and mini-games, but not the full BacToMars videogame (see Table 3). The sessions lasted for 3 hours each day, for a total of 9 hours over the course of the 3-day intervention.

Table 3: Intervention Structure for Group 2 (control non-videogame condition).
Note. Activities in bold indicate activities that only the Group 2 condition engaged in.

DAY OF INTERVENTION	BIOLOGICAL ENGINEERING TOPIC	ACTIVITIES
Day 1 (3 hrs)	What are Natural Resources? What resources are found on Earth and Mars? What is the Environment of Earth and Mars?	Pre-surveys and interviews Engineering building activity using LEGO bricks Vocabulary Discussion: Biology, Engineering, Microbiology Trivia game about environmental resources Read from a children's picture book about microbiology
Day 2 (3 hrs)	What is DNA? How do engineers work with DNA on Earth and on Mars?	Videos and mini-games Debrief about content from videos and mini-games Discussion about DNA and how engineers work with living materials **Read from children's picture book about DNA**
Day 3 (3 hrs)	What are "product genes" and "resource genes"? What is Microbiology?	**Physical game with printed images of "product genes" and "resource genes" from BacToMars videogame** Explore tools of microbiology (e.g. microscope, droppers, petri dishes) Post-Surveys and Interviews

Assessment Instrument

Before and after the curriculum intervention, children completed a survey that consisted of easy-to-read questions and pictures that were completed individually on a computer. The survey addressed the following: attitudes and interest toward science, engineering, bioengineering; self-efficacy and confidence in science abilities; engineering and bioengineering content knowledge; and feedback and opinions of the games and activities. It consisted of a combination of multiple choice, scaled, and free-response questions.

The attitudes portion of the survey was inspired by the Engineering is Elementary (EiE) Engineering and Science Attitudes assessment (Cunningham & Lachapelle, 2010). Engineering is Elementary (www.eie.org) is a classroom-tested curriculum that was designed to increase children's interest in and confidence about engineering. In addition to curricula, EiE also designs and researches student assessments (Cunningham, 2009; Cunningham & Hester, 2007). The EiE Engineering and Science Attitudes Assessment consists of twenty statements, in which children in third through fifth grade are asked to indicate their agreement/disagreement on the five-point Likert scale. Similarly, the survey implemented here included Likert-scaled responses that addressed attitudes and confidence.

Researchers were available to help children with reading questions or understanding the instructions, but they did not give any other prompts or assistance to the children with regard to content.

Interviews

In addition to the surveys, children completed one-on-one interviews with a researcher before and after curriculum implementation. The interview questions consisted of open-ended and opinion-based questions as well as knowledge-based questions. For example, children were asked to provide their own definitions of engineering and bioengineering. They were also asked to reflect on why (or if) science is important and how scientists solve problems in the real world. Finally, children were given the opportunity to share things they liked and disliked about the activities they completed.

Results

Descriptive Findings

The following section presents descriptive findings from the pilot-study evaluation of the BacToMars videogame. Due to the small sample size and pilot-nature of the tools and curriculum intervention used in this study, no analysis for statistical significance was completed. Instead, descriptive statistics were calculated and qualitative quotes were examined with the goal of guiding future work. General trends were analyzed, using comparisons between the BacToMars videogame group and the Control Group.

General knowledge and attitudes trends

In both the Control and the BacToMars groups, children came into the program with a higher level of understanding of engineering than of microbiology or bioengineering (see Table 4). Around 75% of all children were able to correctly define the key term "engineering" in the pre-test in a free response survey question. Children in both groups increased their ability to define microbiology and bioengineering after completing either the control bioengineering curriculum or the BacToMars bioengineering curriculum.

Table 4: Percent of Correct Free-Response Definitions

	ENGINEERING	MICROBIOLOGY	BIOENGINEERING
Control Pre	77.80%	22.20%	22.20%
Control Post	100%	88.90%	77.80%
BacToMars Pre	75%	0%	12.50%
BacToMars Post	75%	50%	37.50%

When it came to children's attitudes, participants in both groups began with a high level of agreement that they like to study science (mean agreement of 4 in both groups on a scale of 1-5 at the pre-test). This makes sense considering the sample was a self-selected group of children who signed up (with their parent's consent) for a science and engineering themed summer program. Children in both conditions increased their belief that they could be a scientist when they grew up and that they have what it takes to be a scientist after participating in this research program (see Table 5). This indicates that the program curriculum, both with and without the BacToMars videogame, had a positive impact on children's attitudes and confidence toward science.

Table 5: Mean Scores on Attitudes Questions Pre and Post

	I LIKE TO STUDY SCIENCE	I THINK I CAN BE A SCIENTIST WHEN I GROW UP	I HAVE WHAT IT TAKES TO BE A SCIENTIST
Control Pre	$\bar{x}$=4.0, std=0.93	$\bar{x}$=3.89, std=1.36	$\bar{x}$=3.89, std=1.27
Control Post	$\bar{x}$=4.22, std=0.83	$\bar{x}$=4.0, std=1.0	$\bar{x}$=4.44, std=1.33
BacToMars Pre	$\bar{x}$=4.0, std=0.75	$\bar{x}$=3.38, std=1.30	$\bar{x}$=2.88, std=1.64
BacToMars Post	$\bar{x}$=4.38, std=1.32	$\bar{x}$=3.75, std=1.49	$\bar{x}$=3.5, std=1.51

Comparing the videogame and control groups

Children's responses to knowledge and attitudes questions at the post-test were analyzed in order to determine any differences or trends between the BacToMars group and the Control Group. Once again, due to small sample size in each group, no significance testing was performed. However, descriptive statistics were calculated in order to look for initial differences.

As noted above, children in both the BacToMars and the control groups had high mean scores on the core attitudes questions including their enjoyment of studying science, their belief that they can be a scientist when they grow up and their belief that they have what it takes to be a scientist (See Figure 13). This indicates that just engaging in developmentally appropriate science activities was impactful on children's attitudes toward science. The biggest difference between the two groups was in their belief that they have what it takes to be a scientist, with children in the Control group having a higher mean level of agreement of 4.44 (*SD*= 1.33) and children in the BacToMars group having a mean level of agreement of 3.5 (*SD*=1.51).

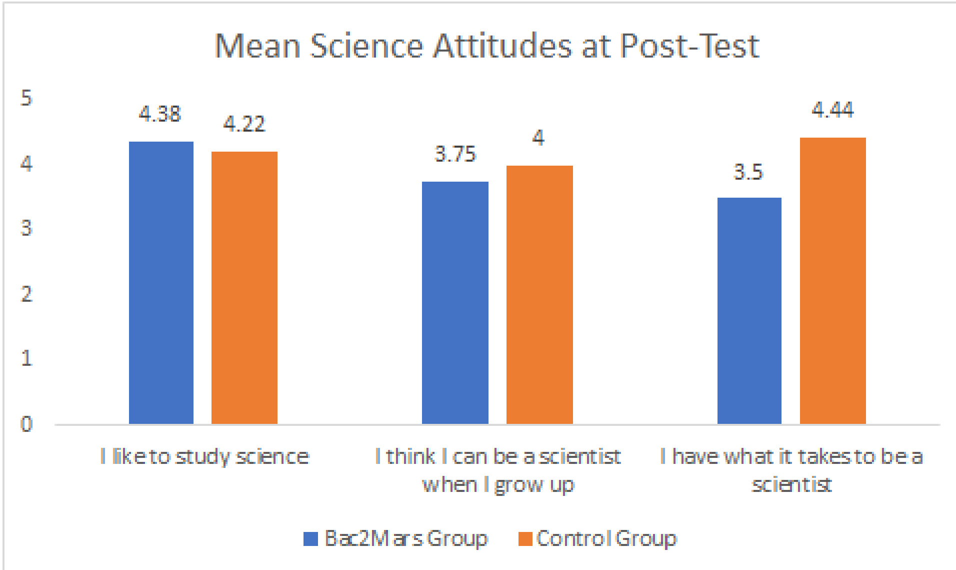

Figure 13. Mean science attitudes at post-test

In the videogame group, female children showed higher initial agreement with these items than male children(regardless of grade), and all children in this videogame groups showed increases of 0.33-1.00 point from Pre to Post assessment (see Figure 14). Children in the control group showed a slightly different pattern, with males having higher initial scores than females and often showing no change from Pre to Post (see Figure 15). Trends in attitude agreement remained consistent regardless of the grade in both groups, with the exception of the item, "I think I can be a scientist when I grow up," in the control group. Children in 2nd-4th grade showed increased agreement from Pre to Post, but males and females in 5th grade showed decreases (see Figure 16). The same pattern was not observed in the videogame group, but that group did not contain any 5th grade children to compare.

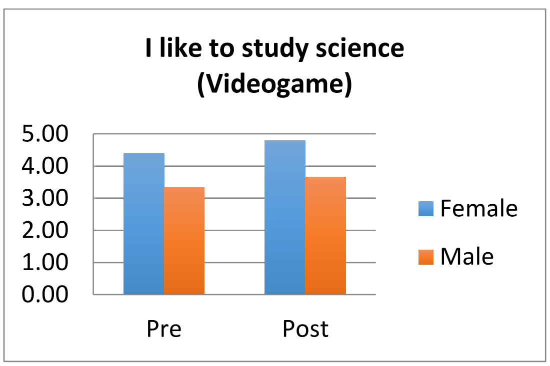

Figure 14. Responses from male and female children in the videogame group to the survey question, "I like to study science".

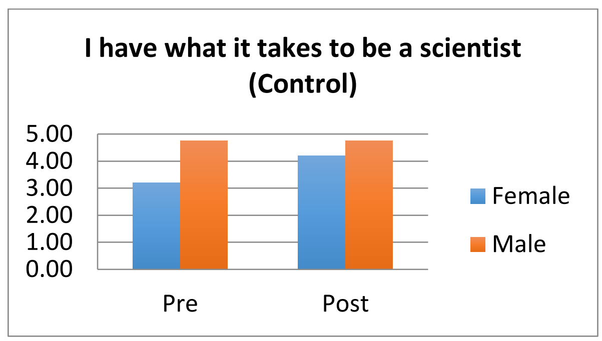

Figure 15. Responses from male and female children in the control group to the survey question, "I have what it takes to be a scientist".

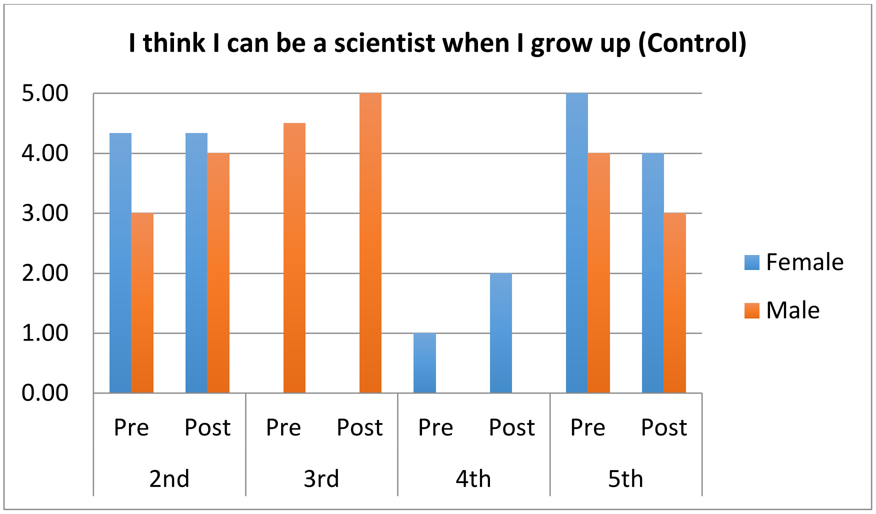

Figure 16. Pre- and Post-responses from male and female children in the control group to the survey question, "I think I can be a scientist when I grow up", organized by grade.

When it came to the knowledge multiple choice questions, results show that, in almost all areas, the BacToMars group had a higher percentage of children who answered each multiple-choice question correctly (See Figure 17). The one notable area of difference in this trend was a question that required identifying the natural resources found on Mars. For this question, only 50% of the BacToMars children were able to correctly answer while 88.9% of the Control group was able to answer it correctly. This may be because the Control Group spent more time learning about Mars since they did not have to learn gameplay mechanics.

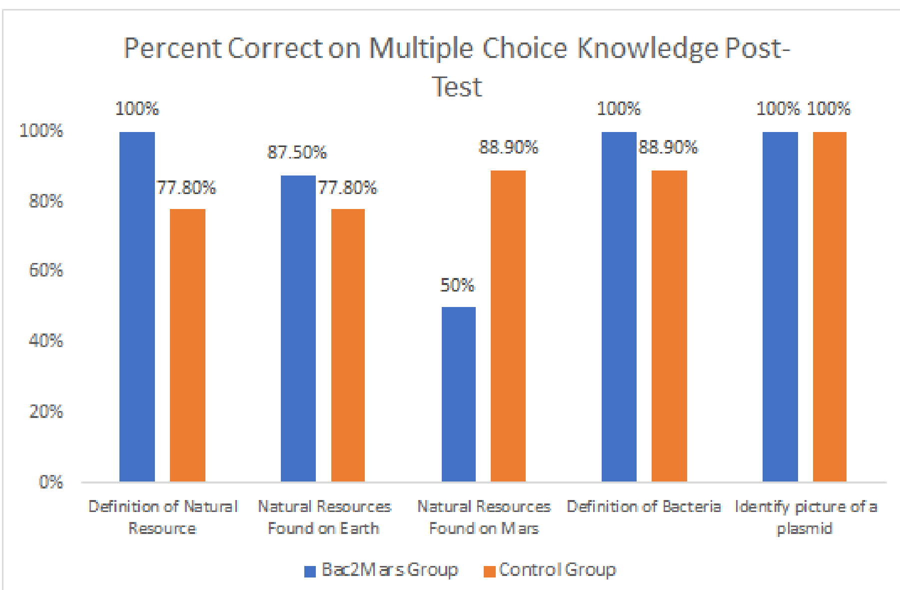

Figure 17. Percent correct on multiple-choice knowledge post-test.

Finally, children's answers to the free response definitions were compared between the BacToMars intervention and Control groups (See Figure 18). Results show that more children in the Control Group were able to correctly provide definitions of all three key-terms including engineering, microbiology, and bioengineering. This was a somewhat surprising finding but it may be due to the fact that children in the Control group were able to spend more time with stories, games, and discussions that reinforced these definitions since they did not engage in videogame play.

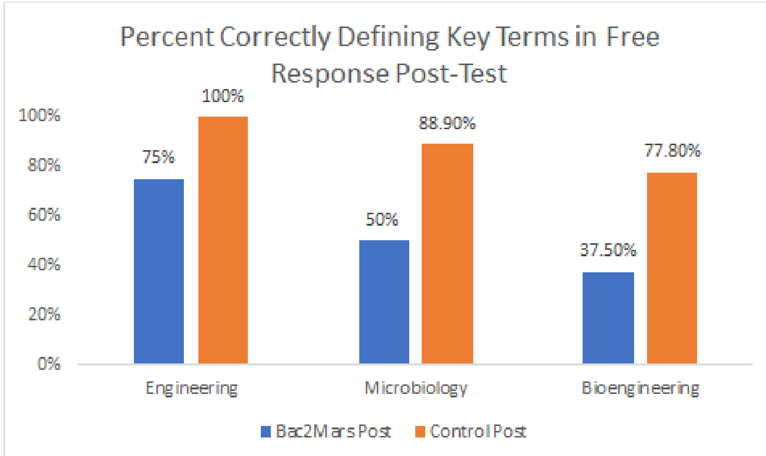

Figure 18. Percent correctly defining key terms in free response post-test

Table 6 shows the aggregate proportion of actual correct out of possible correct responses to all free-response definitions, organized by grade and gender. The control group had a broader diversity of grades represented and both groups had more females than males. In general, males and females in the control group initially showed a higher baseline understanding of engineering, microbiology, and bioengineering. For example, looking only at the 3rd grade males, control males (*n* = 2) initially answered correctly 67% of the time, compared to BacToMars males (*n* = 3) who answered correctly 33% of the time. The control group showed larger increases in understanding from Pre to Post and higher overall understanding after the intervention than the videogame group.

Table 6: Percent of Correct Free-Response Definitions by Gender and Grade

Grade	2nd		3rd		4th		5th		Total	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Control Female	22% (*n*=3)	89% (*n*=3)	-	-	67% (*n*=1)	100% (*n*=1)	67% (*n*=1)	100% (*n*=1)	40% (*n*=5)	93% (*n*=5)
Control Male	0% (*n*=1)	67% (*n*=1)	67% (*n*=2)	100% (*n*=2)	-	-	33% (*n*=1)	67% (*n*=1)	41% (*n*=4)	83% (*n*=4)
BacToMars Female	-	-	17% (*n*=2)	33% (*n*=2)	33% (*n*=3)	67% (*n*=3)	-	-	27% (*n*=5)	47% (*n*=5)
BacToMars Male	-	-	33% (*n*=3)	56% (*n*=3)	-	-	-	-	33% (*n*=3)	56% (*n*=3)

Interview Findings

Children's interviews were examined to find examples of learning, enjoyment, as well as constructive ideas for improving the curriculum and game experience. Illustrative quotes are provided here to demonstrate children's opinions in these areas.

Learning

Children in both the videogame intervention group and the control group expressed learning a lot about the different concepts covered, including Mars, space, biology, engineering, and more. For example, one child stated, "I learned a lot about space" (3rd grade boy). Other children were more specific with the facts that stood out in their memory at the end of the curriculum. One child said, "I learned that there is carbon dioxide on Mars and I always thought there was nothing there" (2nd grade girl). Another child said, "[I learned that] that Mars has soil and sunlight. And that poop is a natural resource!" (3rd grade boy).

Attitudes

Although attitudes towards bioengineering and science were assessed in the surveys, a few children also expressed their attitudes during interviews. For example, one child said that he enjoyed the group discussions about bioengineering, because "I love learning" (3rd grade boy). Another child explained that he would play all of the games and activities from the sessions "with my best friend, because me and him really like science and stuff" (5th grade boy).

Enjoyment

Overall, children expressed that they enjoyed the camp experience as well as playing the BacToMars videogame. For example, one child said, "I really enjoyed coming to this camp" (4th grade female) while another child said, "I had a lot of fun!" (3rd grade female).

When it came to the game experience, children in the game intervention group shared their enjoyment of the BacToMars game. One child explained her enjoyment of the multiplayer feature by saying that, "[The] BacToMars videogame was really fun and you got the choice to play together with other people playing online" (4th grade female). Another child enjoyed learning how to use the natural resources on Mars to create materials that the astronauts in the game needed. This child explained, "my favorite part was figuring out how to use natural resources" (3rd grade male). Finally, some children expressed that they enjoyed the creativity and open-ended features of the game. For example, one child stated, "[I] liked that you could be creative" (3rd grade male).

DISCUSSION

CHILDREN'S LEARNING AND ATTITUDES

From the results presented above, there are three core propositions:

1. Children in both groups improved their attitudes and knowledge about bioengineering.

Bioengineering education is traditionally reserved for high school and college-level education (Linsenmeier, 2003). This intervention confirmed the hypotheses of the research team that children are capable of learning foundational concepts of bioengineering. Furthermore, on the free-response definitions items, children in both groups had high knowledge of engineering before the interventions, but relatively lower knowledge of microbiology and bioengineering. This is probably because in the past decade, engineering education has received an incredible amount of attention, both from the research and the education communities, and learning standards are already in place to support teachers in engineering education (Johri & Olds, 2014; NGSS, 2013).

In addition to improved bioengineering knowledge, children's attitudes about bioengineering in particular and about science in general improved from pre- to post-survey. Specifically, children in both groups were likely to respond at the end of the intervention that they like to study science and that they believe they could be scientists when they grew up. There were apparent differences related to gender among children in the control group with girls showing higher scores post-intervention and boys showing little change in initial attitudes – with the exception of the question about belief in the ability to be a scientist, which showed decreases among 5th graders regardless of gender. In the videogame group, girls and boys both showed increases from Pre to Post in positive attitudes about bioengineering and science.

This finding is very positive from the perspective of curriculum design. The activities chosen in both intervention conditions were sufficient to foster positive attitudes about bioengineering and increased understanding of core concepts. In both groups, activities included a mix of physical play and games, content-specific discussion time and time for exploring reference resources and creating models about relevant concepts. These design elements draw on developmentally appropriate practice in childhood learning settings, as well as the theoretical framework of Constructionism, which forefronts a philosophy of learning-by-doing (Gestwicki, 2013; Papert, 1980). Future work should aim to develop a diverse library of such teaching resources to aid educators hoping to explore bioengineering with elementary-aged children.

2. Children in the experimental condition reported high enjoyment of BacToMars, particularly the multiplayer version of the videogame.

Children's quotes about the videogame indicate that the game was fun and enjoyable to play and offered chances for creativity and exploration. This suggests that the choice to design the game within the framework of Constructionism was successful (Papert, 1980).

When the children played the game together, they often helped each other with questions or difficulties and kept each other updated on their progress. Children who asked the researchers questions about the game were prompted to ask the other children if they knew the answer or to observe what the other children were doing before the researcher would offer help.

During the multi-player version of the game, children were asked on-screen whether they wanted to continue playing alone or collaborate with other players; all of the children expressed great excitement when this screen appeared and encouraged their teammates to choose the multi-player option. No child chose to continue playing alone. Once this final collaborative level began, children immediately began strategizing on how to split the product creation to effectively win the game. The level of enjoyment of the game qualitatively rose after the multi-player portion of the game began, with one child exclaiming "this is so fun working together!"

The fact that children enjoyed the social and collaborative elements of the game could indicate that there is an element of the social/play experience that may contribute to children's knowledge or attitudes. Although prior research has suggested that boys prefer competitive while girls prefer collaborative games (Agosto, 2004), both boys and girls in this study named the collaborative nature of the multiplayer game as their favorite feature. In future work, it might be interesting to see if a competitive version of the multiplayer videogame is as successful as the collaborative version in engaging of different genders. It is also possible that the collaborative nature of the game served to increase boys' and girls' positive attitudes about science. Future work on technology and curriculum design for this age range should focus on collaborative problem solving as a means to engage children in meaningful bioengineering explorations.

3. Experimental condition children scored higher on multiple-choice questions that used images taken directly from the videogame, while control condition children scored higher on free-response questions about key terms and vocabulary.

This finding is interesting, because it highlights the unique achievements of each group. In the videogame group, children performed slightly higher on questions related to natural resources on earth, the definition of natural resources, and the definition of bacteria. In general, the research team attributes this success to the fact that these questions all used images taken direction from the videogame as responses. A logical explanation is that group 1 children spent more time familiarizing themselves with these images and their meanings. An interesting exception to this trend is that the videogame group performed much lower than control group on a question about natural resources on Mars, which was a major feature of the videogame. This is a surprising finding, but it could be that the group 1 children confused concepts of natural resources and resource genes, or that the small sample size resulted in an outsized outlier effect.

Looking at the control group, they outperformed the videogame group on open-ended questions that required children to define key concepts. This finding seems logical, because this group substituted BacToMars gameplay on day 2 with a reference picture book about bioengineering concepts and on day 3 with a collaborative, conversation-based game about bioengineering. These activities are more focused on verbal communication and discussion, which could have better prepared them for verbal free-response questions.

In light of these findings, the research team concludes that the experimental group demonstrated a slightly stronger understanding of concepts directly addressed in the BacToMars videogame, but that their relatively lower performance on open-ended response questions suggests that they may face challenges generalizing their learning outside of the game. In contrast, the control group's lower multiple choice averages suggest room for improved mastery over game-specific concepts of natural resources and bacteria, but their open-response answers show higher general knowledge of key terms. These findings seem to echo results from previous work with the BacPack museum exhibit, in which participants who worked with tangible interactive tokens recalled information related to general genetic and bacterial re-engineering, while users who engaged with a multi-touch screen were more likely to recall information related to the Mars example used in the game (Loparev, Westendorf, et al., 2017). This pattern suggests that there may be a relation between interfaces (screen-based or tangible) and the type of learning that participants take away (specific to the game context, or generally applicable concepts). Future work on bioengineering educational technologies should consider transfer of concepts beyond the game environment as part of the design process. In terms of design implications, this issue could perhaps be addressed by adding a reflective element to the game design. For example, children might keep a "science log" to track their questions as they play, or the game could end with a prompt to write a letter to a real astronaut to connect the learning "outside" of the game. Curricular design should seek to support videogame play with discussions, physical games and other off-screen connections.

Limitations

A clear limitation of this study is the small sample size. The number of children in each group was too small to draw conclusions from this sample to the larger population or to run statistical analysis on the data. Additionally, the short duration of the intervention, meaning that children's learning outcomes might not represent true knowledge gains. Despite this, the pilot nature of this study allows researchers to draw conclusions about implementing the BacToMars game and the bioengineering curricular interventions.

Future Work

Developers and designers of educational technology should consider the findings here when creating educational solutions. Specifically, children in this study particularly responded to social multiplayer features and visual iconography of the videogame.

The videogame, videos, and minigames will be further developed based on the results of this study. Several small bugs need to be resolved in the game and the biomass level needs to include further scaffolding, as many children had trouble getting past this level without prompting. Some explanations in the videos need to be slightly reworded for clarity.

Future work in bioengineering education interventions should focus on longer intervention times with larger sample sizes to determine lasting educational gains. The improved knowledge and attitudes of both groups suggest that educators and researchers should investigate bioengineering as a potential learning domain for elementary-aged children. Educational technology researchers should also investigate the ability of children to transfer knowledge from technology-specific contexts to situations outside of the digital experience. The field can benefit from design principles that maximize transferable, generalizable learning.

CONCLUSION

This paper has presented a mixed-method investigation of a novel videogame, BacToMars and accompanying educational intervention designed to introduce $N = 17$ elementary-aged children to concepts of biological engineering. The study aimed to identify children's attitudes and knowledge about bioengineering and related sub-disciplines of engineering and microbiology, using a questionnaire and interview both before and after the intervention. Children were assigned to either an experimental (videogame) or a control (non-videogame) condition. After a 3-day (9 hour) intervention, all children showed improved understanding and attitudes about bioengineering. Children in the experimental group scored slightly higher on multiple-choice survey questions that corresponded to concepts from the videogame, such as the definition of bacteria and natural resources. Children in the control condition scored slightly higher on free-response questions about the definitions of key terms, such as engineering and microbiology. This suggests that the BacToMars game may be an engaging technological tool to support learning in specific areas of bioengineering.

Overall, children in both conditions showed improvements in bioengineering knowledge and attitudes. The findings from the two groups highlight the relative affordances of a videogame-enriched curriculum to increase content knowledge and draw connections to relevant out-of-game knowledge. Children were highly engaged and curious while playing the BacToMars game and the multiplayer version especially evoked many of the collaborative, open-ended experiences that Constructionist learning tools foster (Papert, 1980). This study confirms prior research, that curricular interventions with a mix of activities and opportunities (e.g., video clips, mini-games, low-tech activities) to engage in the content are highly beneficial for learning (Stieler-Hunt & Jones, 2015). Additionally, we have also confirmed findings on the benefits of collaborative multiplayer game-based learning for engaging children (Kao et al., 2005) and extended this to include increased positive attitudes toward the game's learning content. The learning that occurred in the control group proves that videogames are not a required feature of a science-themed curriculum. However, the combination of in-game and out-of-game experiences results in relatively similar levels of learning, while heightening children's engagement and enjoyment of the learning process.

The BacToMars game showed promise as an engaging and fun way to engage children in applied concepts of bioengineering when coupled with a developmentally appropriate curriculum for elementary-aged children. However, children in each group showed differential learning outcomes. Specifically, children who played with BacToMars scored higher on multiple-choice questions about specific concepts related to Mars and bioengineering, while children in a control condition scored higher on free-response questions about key terms and vocabulary. Future versions of BacToMars and other educational videogames should focus on developing interface elements to transfer knowledge beyond the context of the game scenarios. Overall, these results are promising for educational applications of bioengineering, a novel field that is just emerging as a potential domain in interdisciplinary STEAM curricula for young children.

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REFERENCES

Agosto, D. E. (2004). Girls and gaming: A summary of the research with implications for practice. *Teacher Librarian*, *31*(3), 8.

Barone, J., Bayer, C., Copley, R., Barlow, N., Burns, M., Rao, S., … Players, N. (2015, June). Nanocrafter: Design and evaluation of a DNA nanotechnology game. In *Proceedings of the 10th International Conference on the Foundation for Digital Games,* FDG 2015, Pacific Grove, CA, USA. Society for the Advancement of the Science of Digital Games.

Bers, M. U. (2018). *Coding as a playground: Programming and computational thinking in the early childhood classroom*. New York, NY: Routledge.

Clements, D. H., & Sarama, J. (2003). Strip mining for gold: Research and policy in educational technology—A response to "Fool's Gold". *AACE Journal, 11*(1), 7-69.

Cunningham, C. M. (2009). Engineering is elementary. *The Bridge*, *30*(3), 11-17.

Cunningham, C. M., & Hester, K. (2007, March). Engineering is elementary: An engineering and technology curriculum for children. In *American Society for Engineering Education Annual Conference & Exposition,* Honolulu, HI.

Cunningham, C. M., & Lachapelle, C. (2010). The Impact of Engineering is Elementary (EiE) on Students' Attitudes Toward Engineering and Science. In *American Society for Engineering Education Annual Conference and Exposition,* Louisville, KY.

Corbett, C., & Hill, C. (2015). *Solving the equation: The variables for women's success in engineering and computing*. Washington, DC: The American Association of University Women.

de Freitas, S. (2006a). *Learning in immersive worlds: A review of game-based learning*. London, UK. Report prepared for JISC e-learning and pedagogy experts group. Retrieved from: http://researchrepository.murdoch.edu.au/id/eprint/35774/1/gamingreport_v3.pdf

de Freitas, S. (2006b). Using games and simulations for supporting learning. *Learning, Media, and Technology, 31*(4), 343-358. https://doi.org/10.1080/17439880601021967

Endy, D. (2005). Foundations for engineering biology. *Nature*, *438*(7067), 449. https://doi.org/10.1038/nature04342

Gestwicki, C. (2013). *Developmentally appropriate practice: Curriculum and development in early education*. Cengage Learning.

Greenfield, D. B. (2015). Assessment in early childhood science education. In K. C. Trundle & M. Sackes (Eds,). *Research in early childhood science education* (pp. 353-380). Netherlands: Springer. https://doi.org/10.1007/978-94-017-9505-0_16

Hill, C., Corbett, C., & St Rose, A. (2010). *Why so few? Women in science, technology, engineering, and mathematics*. Washington, DC: American Association of University Women.

Hoffmann, L. (2009). Learning through games. *Communications of the ACM*, *52*(8), 21-22. https://doi.org/10.1145/1536616.1536624

Joan Ganz Cooney Center (2016, November). *Games and learning publishing council.* Retrieved from http://www.joanganzcooneycenter.org/initiative/games-and-learning-publishing-council-analyzing-a-rising-sector/

Johnson, C. C., Peters-Burton, E. E., & Moore, T. J. (Eds.). (2015). *STEM road map: A framework for integrated STEM education*. Routledge.

Johri, A., & Olds, B. M. (Eds.). (2014). *Cambridge handbook of engineering education research*. Cambridge University Press.

Kafai, Y., Telhan, O., Hogan, K., Lui, D., Anderson, E., Walker, J. T., & Hanna, S. (2017, June). Growing designs with biomakerlab in high school classrooms. In *Proceedings of the 2017 Conference on Interaction Design and Children* (pp. 503-508). ACM. https://doi.org/10.1145/3078072.3084316

Kao, L., Galas, C., & Kafai, Y. B. (2005). *"Totally different world": Playing and learning in multi-user virtual environments*. In Proceedings of DiGRA 2005 Conference. Retrieved from http://www.digra.org/wp-content/uploads/digital-library/06275.00211.pdf

Keasling, J. (2006, March). The promise of synthetic biology. In *Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2005 Symposium* (p. 83). National Academies Press.

Kuldell, N., Bernstein, R., Ingram, K., & Hart, K. M. (2015). *BioBuilder: Synthetic biology in the lab*. Sebastopol, CA: O'Reilly Media, Inc.

Lee, S. A., Bumbacher, E., Chung, A. M., Cira, N., Walker, B., Park, J. Y., Starr, B., Blikstein, P., & Riedel-Kruse, I. H. (2015, April). Trap it!: A playful human-biology interaction for a museum installation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 2593-2602). ACM. https://doi.org/10.1145/2702123.2702220

Linsenmeier, R. A. (2003). What makes a biomedical engineer? *IEEE Engineering in Medicine and Biology Magazine, 22*(4), 32-38. https://doi.org/10.1109/MEMB.2003.1237489

Loparev, A., Sullivan, A., Verish, C., Westendorf, L., Davis, J., Flemings, M., Bers, M.U., & Shaer, O. (2017). BacToMars: Creative engagement with bio-design for children. *In the Proceedings of the ACM Conference on Interaction Design and Children (IDC) 2017*. Stanford, CA, USA. https://doi.org/10.1145/3078072.3084334

Loparev, A., Westendorf, L., Cho, J., Flemings, M., Scholze, A., Littrell, R. & Shaer, O. (2017). BacPack: Exploring the role of tangibles in a museum exhibit for bio-design. In *Proceeding of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI 2017)* (pp. 111-120). ACM. https://doi.org/10.1145/3024969.3025000

Menezes, A. A., Cumbers, J., Hogan, J. A., & Arkin, A. P. (2015). Towards synthetic biological approaches to resource utilization on space missions. *Journal of the Royal Society Interface*, *12*(102), 20140715. https://doi.org/10.1098/rsif.2014.0715

Metz, S. S. (2007). Attracting the engineers of 2020 today. In R. J. Burke, M. C. Mattis, & E. Elgar (Eds.), *Women and minorities in science, technology, engineering and mathematics: Upping the numbers* (pp. 184-209). Northampton, MA: Edward Elgar Publishing. https://doi.org/10.4337/9781847206879.00018

National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8*. National Academies Press.

Next Generation Science Standards. (2013). *Lead state partners*. Retrieved from https://www.nextgenscience.org/lead-state-partners

Okerlund, J., Segreto, E., Grote, C., Westendorf, L., Scholze, A., Littrell, R., & Shaer, O. (2016, February). Synflo: A tangible museum exhibit for exploring bio-design. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (pp. 141-149). ACM. https://doi.org/10.1145/2839462.2839488

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas.* New York, NY: Basic Books, Inc.

Planta, J., Xiang, X., Leustek, T., & Messing, J. (2017). Engineering sulfur storage in maize seed proteins without apparent yield loss. *Proceedings of the National Academy of Sciences*, 201714805. https://doi.org/10.1073/pnas.1714805114

Rampey, B. D., Dion, G. S., & Donahue, P. L. (2009). NAEP 2008: Trends in Academic Progress. NCES 2009-479. *National Center for Education Statistics.*

Reardon, S. (2015, November). Leukaemia success heralds wave of gene-editing therapies. *Nature: International Weekly Journal of Science, 527*, 146-147.

Reynolds, A. J., Temple, J. A., Robertson, D. L., & Mann, E. A. (2001). Long-term effects of an early childhood intervention on educational achievement and juvenile arrest: A 15-year follow-up of low-income children in public schools. *Jama, 285*(18), 2339-2346. https://doi.org/10.1001/jama.285.18.2339

Sandford, R., Ulicsak, M., Facer, K., & Rudd, T. (2006). *Teaching with games: Using commercial off-the-shelf computer games in formal education.* Bristol: Futurelab.

Shaer, O., & Hornecker, E. (2008). Tangible user interfaces: Past, present, and future directions. *Foundations and Trends in Human-Computer Interaction, 3*(1-2), 1-137. https://doi.org/10.1561/1100000026

Shetty, R. P., Endy, D., & Knight, T. F. (2008). Engineering BioBrick vectors from BioBrick parts. *Journal of Biological Engineering*, *2*(1), 5. https://doi.org/10.1186/1754-1611-2-5

Smolke, C. D. (2009). Building outside of the box: iGEM and the BioBricks Foundation. *Nature Biotechnology*, *27*(12), 1099-1102. https://doi.org/10.1038/nbt1209-1099

Steele, C. M. (1997). A threat in the air: How stereotypes shape intellectual identity and performance. *American Psychologist, 52*, 613– 629. https://doi.org/10.1037/0003-066X.52.6.613

Stieler-Hunt, C., & Jones, C. M. (2015, May). *A model for exploring the usefulness of games for classrooms.* Paper presented at the DIGRA Conference on Diversity of Play. Retrieved from http://www.digra.org/digital-library/publications/a-model-for-exploring-the-usefulness-of-games-for-classrooms/

Strawhacker, A. L., & Bers, M. U. (2015). "I want my robot to look for food": Comparing children's programming comprehension using tangible, graphical, and hybrid user interfaces. *International Journal of Technology and Design Education, 15*(3). pp. 293-319. https://doi.org/10.1007/s10798-014-9287-7

Sullivan, A. & Bers, M. U. (2016). Girls, boys, and bots: Gender differences in young children's performance on robotics and programming tasks. *Journal of Information Technology Education: Innovations in Practice, 15,* 145-165. https://doi.org/10.28945/3547

Sullivan, A., Strawhacker, A., & Bers, M.U. (2017). Dancing, drawing, and dramatic robots: Integrating robotics and the arts to teach foundational STEAM concepts to young children. In M. S. Khine (Ed.), *Robotics in STEM education: Redesigning the learning experience.* Springer Publishing. https://doi.org/10.1007/978-3-319-57786-9_10

Tech Museum of Innovation (2014). *e-pixels.* Retrieved from: http://2014.igem.org/Team:The_Tech_Museum

Tech Museum of Innovation (2016, March). *The Tech Museum of Innovation opens first interactive bioengineering exhibit this week* [Press Release]. Retrieved from https://www.thetech.org/press-release-tech-museum-innovation-opens-first-interactive-bioengineering-exhibit-week

Weiss, R. (2001). *Cellular computation and communications using engineered genetic regulatory networks.* Cambridge, MA: Massachusetts Institute of Technology.

Zewe, A. (2016, November). *Harnessing bacteria to fight ocean pollution.* Harvard School of Engineering and Applied Sciences: News & Events. Retrieved from: https://www.seas.harvard.edu/news/2016/11/harnessing-bacteria-to-fight-ocean-pollution

BIOGRAPHIES

Amanda Strawhacker is a Ph.D. student in Child Study and Human Development at Tufts University, with the Devtech Research Group. She works under Professor Marina Umaschi Bers of the DevTech Research Group, where she also earned her M.A. researching programming and robotic experiences for young children (Kindergarten through 2nd grade). Previously, she served as the Project Coordinator of the ScratchJr Research Project and as the DevTech Lab Manager. Currently, Amanda's research focuses on designing tools and spaces to engage young children in foundational concepts of computer science, educational makerspaces and bioengineering.

Dr. Amanda Sullivan is the Associate Director of the Early Childhood Technology (ECT) Graduate Certificate Program at Tufts and a postdoctoral researcher with the DevTech Research Group. She has a Master's and Ph.D. in Child Development from the Eliot-Pearson Dept. of Child Study & Human Development at Tufts University where she specialized in educational technology for young children. Amanda's research focuses on exploring gender differences in STEM (Science, Technology, Engineering, Math) fields and developing strategies for engaging girls and women in technology and engineering.

Clarissa Verish is an engineer at the Human Computer Interaction Lab at Wellesley College. She graduated from Wellesley in December 2016 with a degree in Chemistry. She is interested in children's engagement with science through tangible and digital interfaces

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Orit Shaer is the Class of 1966 Associate Professor of Computer Science and director of the Media Arts and Sciences Program at Wellesley College. She is also the founder and director of the Wellesley Human-Computer Interaction Lab. Her research focuses on the application of novel human-computer interaction styles including virtual and augmented reality; tangible, gestural, tactile and multi touch interaction for STEAM education. She is a recipient of various awards including a National Science Foundation CAREER Award, Luce Foundation Professorship, Agilent Technologies Research Award and Google App Engine Education Award.