BacToMars: A Collaborative Video Game for BioDesign

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Abstract: We present BacToMars, a collaborative multiplayer educational video game that engages elementary school children in creative bio-design. We describe the design of the game, its learning goals, and findings from its preliminary evaluation when deployed in informal settings accompanied by a curricular intervention. Our findings shed light on how children play a collaborative multiplayer game while co-located, and on the potential of collaborative video games as a tool for teaching biological engineering to young children and for making a positive impact on their attitudes towards science.

Introduction
Bioengineering is an emerging area at the forefront of science and technology, with far-reaching consequences for addressing important real-world problems related to space travel, food production, energy, and medicine. To date, concepts related to bioengineering are not yet introduced in school curricula until late middle school or high school (National Research Council, 2013). However, introducing children earlier to this burgeoning field at the intersection of science and engineering could foster interdisciplinary thinking and positive attitude towards STEM (science, technology, engineering, and math) (Strawhacker et al., 2018). To expose children in primary school to the excitement, challenges, and core ideas of biology engineering, we developed a collaborative video game, BacToMars, to engage elementary school children in biodesign activities, giving them a playful way to learn concepts that were traditionally considered too complex. We describe its design and implementation in detail and share findings from its evaluation.

Background
Bioengineering is a multidisciplinary field at the intersection of engineering and biology, which produces biology-based solutions to real-world problems. Despite the importance and promise of bioengineering, its foundational concepts are not introduced to students until at least middle school (National Research Council, 2013). Young children are able to learn core concepts surrounding bioengineering (Bers, 2017; Clements & Sarama, 2003) and can engage meaningfully in foundational concepts of engineering design (Auerbach & Silverstein, 2003; Bers, 2012). Researchers have created engineering toys that are screen-free, tangible, interactive platforms that leverage children's ability to learn-by-doing (Ainsworth, 2006; Bers, 2012; Strawhacker & Bers, 2015; Verish et al., 2018). Bioengineering is a promising field for engaging young students' imaginations because it combines the open-endedness of engineering with the constraints of a modular building system.

Related work

Bioengineering concepts
Elementary-aged children (2nd-5th graders) are at a prime age to understand key foundational concepts of bioengineering. Bioengineering combines STEM concepts that are already required in most learning standards for this age range (National Research Council, 2013; Common Core State Standards Initiative, 2013). In spite of the evidence about developmental readiness, bioengineering is likely not taught at this age due to a lack of teaching tools available to educators. The few existing educational tools and initiatives that teach bioengineering are designed for students in high school and beyond (Barone et al., 2015; Kafai et al., 2017).

Collaborative game-based learning
Children can master complex content when learning tools are designed to leverage their intuitive understanding and logic about the world (Druin, 2010), to maximize learner engagement and understanding by offering open-ended problems requiring creative solutions (de Freitas, 2006; Hoffmann, 2009), and to avoid issues of traditional

academic structure and inflexibility (Sandford et al., 2018). Game-based learning can be supported by collaborative interactions (de Freitas, 2006; Steinkuehler, 2006, Okerlund et al., 2016). Multi-player science games can offer opportunities for playfulness, collaboration, and motivation (Kao et al., 2002), foster use of collectivist and positive language (Wise et al., 2017), and encourage emergent leadership styles (Sun et al., 2017).

Design goals

BacToMars is based upon a research paper that explores how bioengineering can be used to facilitate manned exploration missions to Mars (Menezes et al., 2015). BacToMars allows children to create genetic programs for bacteria to sustain human life on the planet. Through collaboration with educators, we have identified specific learning goals for elementary school students (2nd-5th grade) to engage with bionengineering concepts: (L1) Introduce basic concepts of genetics, focusing on genes and DNA; (L2) Facilitate the design of genetic programs that include input and output; (L3) Introduce the foundations of biological engineering methods and scientific protocols to solve real-world problems; (L4) Demonstrate the principles of abstraction; and (L5) Engage players in creative problem-solving of critical challenges related to survival on Mars.

Our design goals for BacToMars were informed by these learning goals and influenced by theories of Constructionism (Papert, 1980) which view "microworlds" as fertile ground for children to cultivate ideas, test hypotheses, and construct new artifacts based on that learning: G1) Facilitate the development of inquiry skills through a hands-on playful experience where users can construct knowledge and apply creative problem-solving; G2) Provide feedback and guidance within the game; and G3) Present opportunities for collaborative learning.

Design of BacToMars

The current version of BacToMars is a result of an iterative design process and close collaboration with both educators and children. Following, we describe the main design of the game.

Goal of the game

Players are tasked with helping a team of astronauts survive on and escape from Mars after their biodome, supplies, and spaceship are destroyed in a dust storm. To do so, players are guided by the main game character, a biological-engineer astronaut, to design bacteria that produce various materials (products) by combining input and output BioBricks, visually represented by interlocking blocks. Input BioBricks make the bacteria consume readily-available resources on Mars, such as carbon dioxide, while output BioBricks produce particular products, such as oxygen. Some combinations are more effective than others.

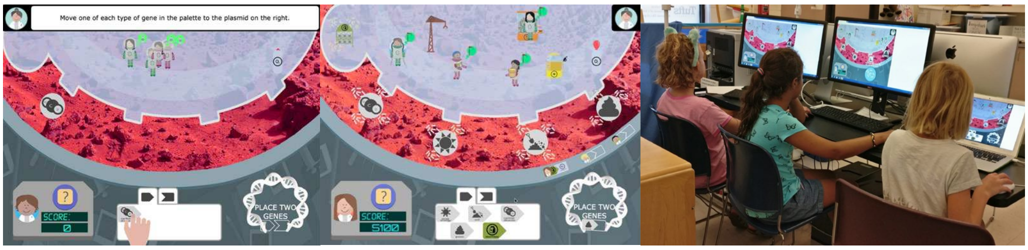

Figure 1. The game space of BacToMars. In the first level (left), players are shown how to play the game. The final, multiplayer interface (center) adds complexity and requires collaboration to complete the game. Children played the multiplayer game at adjacent computers to encourage collaboration (right).

The game space is organized into two main areas, as shown in Figure 1: the Mars landscape with the astronauts' biodome, natural resources, and product levels; and the workbench, where players can access resource and product BioBricks to engineer bacteria, view combination feedback, and see their score and character. Players must keep track of the product levels as they play so that the astronauts do not run out of any supplies. Figure 1 shows the game screen in a beginner level and an advanced level.

Gameplay

We developed BacToMars as a multi-player collaborative game with a curricular supplement consisting of educational videos and minigames to explain the key concepts behind the game. Gameplay starts with a character selection screen, where players can create their character. Single-player scaffolding was integrated in the game, as shown in Figure 1. Players start by making oxygen using carbon dioxide, then are lead through more complex combinations. Once each player completes the scaffolding, all players are asked simultaneously whether they would like to collaborate. If they choose to collaborate, the Build a Launchpad level begins. Gameplay ends when the team has successfully created a launchpad and spaceship. Players are then shown their final scores and team contributions. Throughout gameplay, players can view their individual score and character representation and that of their collaborators. Players work collaboratively in a single biodome to create products, and can view the product yield of all players so each may evaluate the effectiveness of each combination.

Evaluation

Procedure

The BacToMars game was tested during a 3-day informal bioengineering workshop. The research team observed $N = 9$ children (5 girls, 4 boys) in 4^{th} and 5^{th} grade as they explored bioengineering content through digital and traditional learning activities such as physical games, picture books, and robotic construction. Children were divided into groups of three for the collaborative game and sat at adjacent computers, as shown in Figure 1. One group consisted of all girls, one of all boys, and one of mixed gender. In each group, children played the single-player scaffolding levels for approximately 10 minutes, and then continued to play the multiplayer extension for another 10 minutes. Researchers made qualitative observations, videotaped the interactions, and collected pre- and post-task questionnaires, which included questions about the key concepts, an attitudes questionnaire, and questions about their subjective enjoyment. We coded video transcripts for verbal content-specific themes.

Results

Multiplayer gameplay

When children encountered the prompt to either continue to play alone or play collaboratively, all of them chose to play with others and urged their teammates to choose that option. On average, groups played the single-player levels for about 10 minutes, and multiplayer levels for about 8 minutes. In all three groups, the total utterances in the multiplayer levels were greater than in the single-player levels. Both planning (discussion of tasks or roles) and narration (statements of actions or observations) dramatically increased from single-player to multi-player. Questions asked during gameplay were split into two groups: questions asked about how to play the game; and questions about concepts. Explanations were coded as players answering questions for each other. The number of positive interactions (statements of affirmation or excitement) increased between the single- and multiplayer levels. Competitive utterances, such as comparison of scores, also increased.

Usage of content key terms, such as “plasmid” or “bacteria,” were tallied for each group during single- and multi-player game play. In addition, children were asked to define these terms in their pre- and post- task questionnaires. None of the children in our preliminary evaluation used a key term during gameplay, however the percentage of correct definitions did increase in the post-task for five of the six key terms. We also assessed science attitudes before and after gameplay. Average responses for all children, and for boys and girls separately, increased after gameplay. Children were asked a series of free response questions about what they enjoyed most about the week. Multiple children highlighted that they enjoyed the collaborative game the most.

Discussion

The multiplayer aspect of BacToMars facilitated engagement and collaboration, as demonstrated through increased utterances, planning and narration, and positive interactions. We saw an increase in correct definitions of key concepts after completion of the curricular component and gameplay, indicating that young children can indeed learn advanced concepts when presented with developmentally-appropriate curricula and tools. Attitudes scores improved for all children, but the increase in attitudes for girls as a group is promising. Overall, the design of BacToMars was effective at supporting children’s engagement, enjoyment, and learning. Our design of BacToMars demonstrates that collaborative games about real-world challenges are effective learning tools. Research on educational videogames can benefit from the current findings, indicating that providing open-ended, creative play experiences can inform children’s attitudes about learning content. Future work should focus on engaging children through a variety of digital media, including tangible interactions, and should focus on collaborative play as a way to foster bioengineering learning.

Conclusion and future work

Through collaborative gameplay, BacToMars encourages children to place themselves in the role of a bioengineer in order to help a team of astronauts. In conjunction with the educational videos and minigames, BacToMars increased children’s knowledge of key bioengineering concepts. We plan to further develop curricula and novel interfaces to bring the burgeoning area of bioengineering to primary schools.

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