International Journal *of* Designs for Learning
2020 | Volume 11, Issue 2 | Pages 80-95

ESCAPE THE PLANET: EMPOWERING STUDENT DESIGNERS TO CREATE A SCIENCE-BASED ESCAPE ROOM WITH AUGMENTED REALITY

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The American Museum of Natural History (AMNH) in New York City implemented a science-based curriculum pairing augmented reality (AR) with a student-designed escape room experience to support astronomy learning. AR has the potential to simplify complex systems into digestible concepts. Designing an escape room experience provided students with an exciting opportunity to apply their understanding of astronomy concepts. This paper (1) presents a background of the curriculum, our development process, and describes the student-design framework, (2) describes the design of the escape room and the activities to facilitate science learning, (3) discusses how we utilized augmented reality in the course (4) presents design issues and revelations, and (5) proposes future changes.

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https://doi.org/10.14434/ijdl.v11i2.24110

DESIGNING A CURRICULUM THAT USES AN ESCAPE ROOM AND AUGMENTED REALITY TO TEACH ASTRONOMY

The American Museum of Natural History (AMNH) in New York City implemented a science-based curriculum pairing augmented reality (AR) with a student-designed escape room experience to support astronomy learning. This paper (1) presents a background of the curriculum, our development process, and describes the student-design framework, (2) describes the design of the escape room and the activities to facilitate science learning, (3) discusses how we utilized augmented reality in the course (4) presents design issues and revelations, and (5) proposes future changes.

How Escape Rooms Facilitate Collaborative Learning

An escape room places participants in a narrative-driven experience where they must solve physical or digital puzzles to "escape." These puzzles often include a series of challenges (e.g., find a lock combination, locate a key, input a password, etc.) where the players are under the pressure of a short time limit. They must communicate with one another, make quick decisions, weigh consequences, and take healthy risks to escape the room and win.

Nicholson (2015) describes the value of escape rooms as ideal spaces for informal learning, as they offer clues and props situated in a contextually relevant space that can facilitate a sense of immersion and a narrative that ties to specific learning content. Such affordances could be harnessed in a classroom because escape rooms are a collaborative process in the pursuit of a learning goal (Nicholson, 2015). Situating these gamified experiences within a collaborative student-design framework can empower students to think critically about science while applying their understanding of astronomical concepts as they design the escape room. This is because they are in control of the experience and must work together to make decisions related to embedding content, educational goals, and functionality.

Dunleavy et al. (2008) explain that student engagement and learning can also be shaped by their participation in the classroom. In addition, collaborative design tasks like those used in this course emphasize the importance of skillsets that are applicable to outside contexts. This can include connecting instructional content to interactive experiences, implementing and iterating on ideas based on user feedback, and team building (Claypool, & Claypool, 2005). Collaborative learning has also shown to generate higher achievement outcomes, higher-level reasoning, and better retention of content when compared to traditional instructional approaches (Johnson and Johnson (1987).

Why Augmented Reality?

Embedding immersive and engaging virtual experiences into the classroom has strong implications for student learning and science engagement. Such benefits include learning through collectively seeking and synthesizing instructional content, active learning based on situated experiences in applied contexts (Dede, 2005), and the capacity to facilitate kinesthetic learning via rich, sensory-spatial contexts (Dunleavy et al., 2008).

This form of mediated immersion can augment student experiences and interactions in the classroom (Dede et al., 2010). For example, while discussing in a group activity a comet's potential trajectory as it navigates our solar system, students could wear a HoloLens to trace the path of the virtual comet floating in the classroom in real-time. This simulation is then paired with hands-on learning activities and reflection exercises to solidify student understanding of astronomy content further. As a result, these authentic, meaningful, and engaging, contextual learning experiences can support the exploration of science content and scientific inquiry (Clarke, & Dede, 2007). These learning opportunities may be more impacting when compared to watching a movie or listening to a lecture in a typical classroom.

COURSE BACKGROUND

In collaboration with AMNH's Youth Initiatives and Science Bulletins programs, the four-day experimental course, titled *Escape the Planet,* introduced 17 high school students to astronomy topics, digital datasets, and design thinking. The course occurred for only four days because its timing coincided with students completing their high school Regents Examinations-a required New York standardized test. The museum makes frequent use of its resources to design experimental coursework that can engage learners of all ages.

As part of the curriculum, students created a prototype escape room designed to teach astronomy concepts through puzzles and AR simulations of solar systems and constellations. We intended to use the escape room as a prototype for future science-based programs and museum exhibits.

Students attended the course at the museum, and classes were separated by morning and afternoon sessions. Each session lasted for two hours with a lunch break in between. The course was managed by a pair of teachers, one who focused on educating students about the astronomy content, while the other taught students about design thinking and game development for constructing the escape room.

COURSE DEVELOPMENT PROCESS, AND THE STUDENT-DESIGN FRAMEWORK

Course Development Process

The development of the curriculum occurred approximately one and a half months before the launch of the course. The design team was comprised of five members who handled the development process and oversaw the course. Two teachers designed the course curriculum; one focused on the astronomy learning content, while the second worked on the game design portion. An in-house digital artist developed the AR simulations and oversaw their application. Two additional team members managed the project and ensured everything progressed smoothly.

Initial meetings outlined the course structure, learning objectives, technology needs, and the development schedule of the AR simulations. We knew the prototype escape room was our primary deliverable, but there was uncertainty about how closely connected it should be to the educational content. With a limited class schedule, there was only so much that students could learn, and this would have to be balanced with the time required to build the escape room.

To counteract this, we began to view the design of the escape room as an extension of the learning experience. Because the students would design it, this presented them with an enticing opportunity to apply their understanding of the course content as they endeavored to create the experience. In effect, we addressed two problems with a single solution.

We also wanted to utilize the HoloLens devices as an educational tool and a part of the escape room. If the deliverable was successful, and we could further iterate on the design for public consumption, the devices could act as a popular draw to engage visitors. We also believed AR could be beneficial in enhancing educational environments via interactive simulations. Given the confines of the schedule, and we only had two devices total, we needed to strategize their implementation and timing for student use.

Rather than permit students free use of the devices during class, we opted for using simulations that could be paired with instructional content (i.e., constellations and solar systems). Fortunately, we possessed two non-AR programs from previous museum exhibits, and the digital artist worked on converting these programs to be compatible with the

HoloLens. With these concerns addressed, we dedicated the remainder of our preparations on the curriculum.

Each class day was designed with its own learning goals and activities that taught students (1) core astronomy concepts, (2) the iterative design process as it related to the escape room project, (3) how to embed learning activities into a designed experience, and (4) how AR can enhance their learning through situated activities (see Table 1 for the course schedule). For example, one particular class taught students about constellations (i.e., types, planetary rotations), and we then had students design simple puzzles that can teach those same concepts.

The Microsoft HoloLens

Two Microsoft HoloLens devices were made available for use in our course. The HoloLens is a head-mounted AR unit that overlays real environments with virtual artifacts (e.g., pictures, 3D objects, and programs). We intended to use them as instructional tools students could leverage to apply their understanding of astronomy concepts. Additionally, we sought to implement them into the escape room design to highlight the interactive simulations that paired with embedded science content and learning goals.

While we only had two units at our disposal, we preferred the HoloLens over other AR-capable devices such as cellphones. The simulations from the previous exhibits we wanted to convert were not readily compatible with phones. Additionally, we were concerned that personal phones had to be volunteered so we could use them for the course, and this would create issues as it progressed. In addition, cellphone AR apps would drain phone batteries quickly. This would make their use both in class and in the escape room far more difficult. While two devices is not ideal for a class this size, we already had them available from previous initiatives.

Black Hole Theater

The Black Hole Theater served as our space for the escape room prototype. This theater screens astrophysics films as part of our main Black Hole exhibit. The space is approximately 15 feet by 25 feet and was large enough to accommodate our class size. The room contained black walls, rows of benches, and an overhead projector pointing to a large screen. Regrettably, the benches were unmovable, so students had to work around them. We took special precautions and prevented them from moving around the theater while using the HoloLens unless guided by another. Typical escape rooms do not need such a large space and can be empty rooms containing the necessary props and puzzles. However, we wanted to give students as much room to work as possible.

Science Content Curriculum

We designed the curriculum on the assumption that students possessed a basic competency in astronomy. Because the class only lasted for four days, we could not delve deeply into astronomy topics as much as a regular classroom. As such, we chose concepts that reinforced student's prior knowledge and could be generalizable to a wider audience. For this reason, we focused on two core astronomical concepts; solar systems and constellations.

Specifically, we wanted students to (a) model the solar system with accurate planet sizes, distances, and locations, (b) recognize constellations (e.g., nebulae, galaxies, and clusters) as two-dimensional (2D) entities in a three-dimension (3D) plane, and (c) identify objects located in constellations other than just stars or planets. We selected these concepts because of their importance in astronomy education, adherence to the New York State Science Core Curriculum, and connection to current AMNH exhibits.

Educators introduced these astronomy concepts to students via hands-on learning activities (e.g., Earth as a Peppercorn and Human Orrery), "think-pair-share" discussion exercises, and class lectures. Think-pair-share exercises are collaborative activities that help students articulate ideas or address problems by working with a partner (Lyman, 1987).

Technology Implementation

The AMNH frequently designs digital exhibits as part of its usual operation, and we repurposed two simulations from previous museum initiatives. These simulations were originally Windows-based computer programs without any attached input methods the HoloLens supported (e.g., gaze and gesture inputs). The Digital Universe dataset served as the baseline model for each digital simulation, and it was used for the museum's Hayden Planetarium exhibits. One

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY
MORNING SESSION	What's in Space? Learning activities	Constellations, astronomy via puzzles	Production day, narrative pitch, AR inclusion	Iterate changes, production, debrief
AFTERNOON SESSION	Puzzles, AR, and Escape Room Trial	Intro project, design breakout, work w/ AR	Build, mockup run through, AR deliverables	Expert playtest, school playtest, feedback

TABLE 1. A snapshot of the course schedule.

FIGURE 1. A student learning how to use the HoloLens. Photo credit: American Museum of Natural History

simulation highlighted several popular constellations (e.g., Orion, Ursa Major, and Taurus), while the second featured our solar system.

Modifications for each simulation were created in *Unity*, a cross-platform application to develop games and simulations and coded in C Sharp (C#) by the digital artist.

For example, in the programs that came with the devices, the fixed camera position and perspective on the screen did not allow users to view constellations or the solar system at different angles. These were altered to be compatible with the HoloLens so students could move around the environment to view the virtual representations. This was necessary for the escape room, as participants would move around the Black Hole Theater. This compatibility process took approximately one week and was the major component of the pre-production work the digital artist carried out prior to the start of the course.

Integrating the programs into the HoloLens is similar to the process of creating and installing applications on Windows devices. The digital artist created a Windows application on a personal laptop, connected the HoloLens, and deployed them onto the device. If updates were warranted based on feedback (e.g., content, camera angles, voice commands), we repeated the process.

The digital artist scripted all user interface functions to make them as built-in features in the app. This enabled users to open each custom program to play the puzzles as one would do to play games on their smartphone. Because the digital artist had to make the changes to these simulations, students did not design the elements present in the HoloLens.

In addition to the HoloLens simulations we developed, we also used an application called *Uniview*, which turns astronomy data into interactive visual experiences. Our decision to include this program into the course served several objectives; (1) The program helped teach students about data visualization and how constellations/solar systems are three-dimensional (3D) entities, and (2) the program could inform puzzle design and HoloLens use for the escape room project. Similar to the HoloLens simulations, the Digital Universe dataset also served as the source for the *Uniview* experience.

Educators as Designers

A pair of teachers managed the class lectures and design exercises, while the digital artist to assist in classroom management. While both teachers facilitated the learning process and guided the escape room construction, each fulfilled a particular role as they managed the course. One teacher was designated the astronomy expert, who taught the courses' astronomy content, created astronomy-based puzzles to promote design thinking, and ensured the scientific accuracy of the escape room (e.g., learning content, narrative, puzzles, etc.).

The second teacher was the game expert, who introduced the game concepts, assisted students in designing the puzzles and connecting them to the science content, and helped balance the playability of the escape room design. The digital artist developed the AR virtual simulations in preparation for the course, worked with students to modify them based on their recommendations as they constructed the escape room, and worked on incorporating into the play space.

Educators as Collaborators

We implemented a student-design framework to empower students to apply their understanding of astronomy as they created an escape room experience with an AR component. We wanted students to view educators as collaborators and knowledge resources, not a source for direction or authority. While we expected students to lead the project's development and make all final decisions, we anticipated they would have trouble in assuming a leadership role. To boost student confidence and agency as designers, we (a) used targeted reflection questions, (b) repeated motivational prompts, and (c) communicated in ways to foster exploration.

Targeted reflection questions focused on their team roles, design processes, and contributions. We articulated questions to include phrases such as, "What were your decisions…," "How did you address…," and "What do you recommend…" We focused on students' processes of embedding instructional content into the experience, and in what ways the escape room connected to the course learning goals.

We understood the value of student motivation and were mindful that students might get discouraged during the design process. To reinforce student motivation while they were testing out design ideas, we used phrases such as, "This was your first attempt, maybe try a different approach…" and "This may not have worked out this time, but try it again..." We wanted to reiterate the belief that success may require several attempts, and students should try again until they found a design that suited them--a message reflecting effort over inborn ability (e.g., Dweck, 2000; Murphy & Dweck, 2010).

To foster exploration, we posed hypothetical scenarios for students to imagine how users may interact with their designs. For example, we encouraged them to think about issues of clarity (e.g., "Does this make sense…" "How will this work…"), how well designed it is, and technology (e.g., use of the AR device, virtual simulations, etc.). We were also quick to remind students that they were in control and would make all final decisions related to the project.

STUDENT DESIGN PROCESS—TRANSITIONING STUDENTS TO BECOMING DESIGNERS

Preparing students to transition into the role of designers meant that the teachers also had to adjust their status in the class. Because we wanted students in control of the design process, teachers had to become collaborators who worked with and supported the students. To accomplish this, we continually reinforced our message of empowering students to make design decisions and experiment with potential possibilities.

We encouraged students to explore options and use any available resources to pursue their design goals. We also communicated to them our expectations for the project; that the student-designers did not have to create a final product, but a playable prototype. This was an important distinction for our student-design framework because it helped alleviate time management issues, information overload, and gave students a realistic and achievable goal.

"Incomplete Information" Concept

Of particular interest to our educational goals was the concept called "incomplete information" inherent within games and escape room scenarios. Meaning, players do not possess full information about the game's content or the other players. For example, if two players are playing a card game, each player could only assume what cards are in their opponent's hands, and have to strategize based on the available information. In an escape room, the game challenges players with puzzles and clues to solve them, but it is up to the player to formulate a solution.

For our purposes in preparing students to design an escape room experience, incomplete information had a dual purpose. The concept helped students work through their design decisions and take healthy risks as they developed the experience. Because they were still learners, they had to rely on their prior knowledge, test ideas, and make any necessary adjustments as needed while developing the escape room and its components.

Incomplete information also helped them embody experiences that scientists have when conducting experiments. Just as players formulate theories and judgments based on available information, so too do scientists make hypotheses and judgments based on similar circumstances (Liang et al., 2006). Pointing out this parallel was an effective approach to pushing students to take risks. We believed that fully immersing them in an escape room context, allowed us to simulate similar challenges and offer students situated situations to apply their knowledge.

DESIGNING AN ESCAPE ROOM USING A SCIENCE-BASED CURRICULUM AND AUGMENTED REALITY

In this section (a) presents the course schedule and paired an "escape room" scenario with the curriculum, (b) discusses how the escape room activities were developed and how augmented reality was implemented, (c) describes design issues, revelations, and constraints, and (d) explores future changes to the design.

Course Design: Day One

The morning session on the first day introduced students to astronomy concepts such as size and distances of planets, orbital rotation predictions, and solar systems. Educators introduced these astronomy concepts to students via hands-on learning activities (e.g., Earth as a Peppercorn and Human Orrery), think-pair-share discussion exercises, and class lectures. Students learned about data and data visualization by interacting with the *Uniview* program on distributed laptops (Windows 10 OS). After the teachers explained how to navigate the virtual solar system, students identified specific planets and calculated how long it took for Saturn to orbit around the Sun.

Game Design Processes

During the afternoon session, students learned about game concepts and mechanics via a class exercise that focused on game components and their design. This introduction included game rules and mechanics (e.g., object interaction, dice rolling, and goal conditions), content, and challenges (e.g., narrative and setting), and user interface (e.g., notifications, instructions, imagery, and graphics). This was an important inclusion because it featured concepts they eventually incorporated into their escape room designs. Additionally, previous student experience with games was disparate, and we had to ensure everyone started with equal knowledge.

While a general understanding of these game aspects was needed, we steered the discussion towards components that would be incorporated into the escape room project. This guided-instruction included types of puzzles, storytelling, and settings that encourage collaboration and fit within a science learning context. For example, we wanted students to design escape room content that incorporated technology, movement, and objects related to solar systems and constellations.

Experiencing Design: Dr. Bore and the Quest for Hope

After we discussed common escape room elements, and how its mechanics could connect to science concepts, we had the students play an actual escape game called Dr. Bore and the Quest for Hope. Before they started, we urged students to think about how the game situated instructional content in applicable contexts (e.g., presented science content, connected puzzles, and narrative). Our goal was for students to view the experience from a designer's perspective rather than as a player.

Provided by the educational game company BreakoutEDU, Dr. Bore and the Quest for Hope was a 35-minute escape room experience that came in a plastic kit containing all of the necessary tools and materials to play. Its portability made it ideal for a classroom space. The included materials transformed the classroom into a laboratory filled with science-based puzzles, posters with invisible ink, secret dates, coded messages, and a goal of acquiring a cure that saves the world from destruction. Students first watched an included video of the Dr. Bore character that introduced the narrative and how to play. They then formed into four separate teams to complete the game competitively.

Once students completed the experience, we reconnected for a class reflection exercise. This was necessary, as we wanted students to avoid simply focusing on gameplay strategies and their experiences. Instead, we asked them how the puzzles were designed (e.g., progression, mechanics, features), how incomplete information affected their communication, and how astronomy content could be embedded into a similar experience. We then began transitioning students to using the HoloLens and working with activities that encouraged design thinking.

Introducing Augmented Reality

Students first experienced augmented reality with the HoloLens via a five-minute training program called "Gestures." Because only two devices were available for the course, students rotated into the tutorial to ensure everyone had the opportunity to use the devices. With the assistance of the digital artist, students learned how to use the device, navigate its virtual interface, and interact with 3D objects

FIGURE 2. A student interacting with the Gestures training simulation. Photo credit: American Museum of Natural History

through physical hand gestures, timed gaze inputs, and voice commands (see Figure 2).

Remaining students formed into groups and given hands-on exercises, such as working with clay models to compare planet sizes, and game-based activities, such as playing cooperative astronomy puzzles that primed them on the upcoming development project. For example, one puzzle illustrated that the latitude of a location is determined by the height of stars above the horizon via images of the night sky. In addition to these puzzles, student groups also played the computer game Keep Talking Nobody Explodes, a cooperative game about disarming bomb puzzles with the assistance of other players reading a separate manual to demonstrate incomplete information. We selected these particular activities because they connected with our vision for the escape room design.

Before class concluded, we asked students to reflect on their experiences with using the HoloLens, as well as how the other activities connected with the day's topic and the Dr. Bore escape room experience. These activities and reflection exercises helped students (a) see how games and puzzles pair with instructional astronomy content, (b) consider how the HoloLens could be used as a tool for learning, and (c) think about how they would design the escape room experience with these components.

Course Design: Day Two

During the morning session, students learned about constellations. The class opened with a discussion activity about student prior knowledge, a diorama presentation that showcased how constellations are artificial constructs based on perspective, and then focused on popular constellations (e.g., Orion's Belt, Taurus, Virgo, etc.) and important features about them (e.g., patterns, star positioning, orbits, etc.).

Students also played several astronomy puzzles designed by the instructors as a way to assist in ideating puzzles that incorporate course learning content. For example, one puzzle was about students finding their location on Earth based on the position of the stars. As students were completing the puzzles, we consistently asked them to consider (a) how the puzzle mechanics called upon their prior knowledge of constellations, (b) what learning goals were embedded into their design, and (c) how this understanding of puzzle design could be connected to a narrative to facilitate an escape room experience. This ensured that students consistently thought and acted like designers.

As we continued to develop their understanding of astronomy content, we moved towards the main purpose of the course, creating a student-designed educational escape room experience. To start them on this path, we first established a series of constraints and expectations. These included; (1) the puzzles had to connect with the course's science content, (2) the experience would last for 5-15 minutes, (3) the narrative needed to take place on Mars because the planet is recognizable and connected to the Hayden Planetarium exhibit, and (4) they only needed to create a working prototype.

Designing an Educational Escape Room Experience

Once guidelines were established, we started students on the design process by first taking them out of the classroom and into the Black Hole Theater. We closed the theater to the public for our class, brought in the students, and offered it to them as their playground to design the escape room. We explained that they could make any change that was not permanent (e.g., hang things on the walls, place props on the floor and benches, etc.) and gave them complete agency to work.

When students returned to the classroom, we placed them in five groups that each focused on creating a paper-based puzzle to generate ideas. The goal of this hands-on breakout session was to help solidify their understanding of the design process and for students to get an idea of how puzzles can teach content. It also helped the students decide on the most promising puzzles to develop later.

We also emphasized that they identify what astronomy concepts they want their puzzles to teach (e.g., orbits, constellations, etc.), and to consider what prior knowledge is needed to successfully complete them. Both teachers patrolled around the classroom to work with students and provide on-demand feedback as needed. After the first breakout session, we reconvened with students to hear about their ideas and wrote keywords on the board. They explained their progress, and we asked them for each puzzle's content area and learning goals. In cooperation with the teachers, the students decided to focus on two distinct puzzles because of the escape room's intended minute duration.

For the second breakout session, students self-selected into four design groups; two puzzle groups, a HoloLens design group, and a narrative/story group. However, before they could start working, the students had to agree on a narrative for why the players start on Mars and how they can escape (see Figure 3). Once they had a general idea of how it would go, each group began working on their assigned component. Aside from the constraints already established, students had relative freedom to construct the story, puzzles, and the environment as they saw fit. Students and teachers worked together to develop the game's plot and narrative in preparation for a pitch presentation with Science Bulletins staff the following day. We believed getting a third opinion on their efforts was an important part of the design process.

While the puzzle groups were mapping out their ideas, we encouraged them to utilize aspects of the paper puzzles they experienced earlier. Each puzzle group was also given access to laptops with the *Uniview* software for additional ideas as needed. For example, students used the program to set the date and time to reflect different configurations of the planets in the solar system and took screenshots of these visualizations. The orientations illustrated optimum and poor configurations for a trip from Earth to Mars, a core component of the narrative and puzzles.

We also encouraged the puzzle groups to use the HoloLenses so their work is better connected with the simulations they would eventually include. This was also an opportunity for them to tell the digital artist about any needed adjustments. For example, puzzle groups made requests such as brighter/clearer look of the starfield, dimmer/thinner constellation lines, and easily recognizable visual and audio responses when the viewer gazes at interactable stars.

The HoloLens group focused on how the device would connect with the puzzles, as well as deciding where in the theater those simulations would appear. Because the students were not developing the virtual simulations due to the C# programming requirements, this group worked closely with the digital artist throughout the rest of the course. Again, while the simulations were already established, students had to decide how they would be used in the escape room.

For instance, they decided that the constellation simulation would be most appropriate for conveying the educational point; that stars exist in the 3D space. They also explored what star info would be a good clue for users to help them solve the puzzle. As a result, they selected three constellations users would see in the HoloLens and be provided with X, Y, Z coordinates to show as clues to deciphering distance from Earth.

At the conclusion of the second breakout session, the class reconvened for a debrief session to discuss their progress and check-in about the next day's pitch presentation. This was also an opportunity to pinpoint any challenges students were experiencing, address questions of learning content accuracy, and discuss deliverable requirements.

Course Design: Day Three

Day three began with a student pitch to the Science Bulletins staff to describe the narrative that would shape the escape room experience, and the puzzles participants would encounter. The purpose of this pitch was to a) ensure that the escape room matched the museum's educational endeavors, b) verify the integrity of the instructional content; c) match the escape room puzzles with real scientific processes, d) put all student groups on the same page to represent a united front, and e) further emphasize the student-designer identity and reinforce that the class worked collaboratively with instructional staff and not subordinately.

Science Bulletins staff recommended a number of changes to the design, but focused much of their attention on the narrative and puzzles. They felt the narrative of crashing on Mars and trying to navigate back to Earth made sense, but they stressed how the methods of doing show should connect with how it would be done in real life. These comments fed into their recommendations on the puzzles; could the players use star charts and similar data to trace a path through the solar system back home? Additionally, they

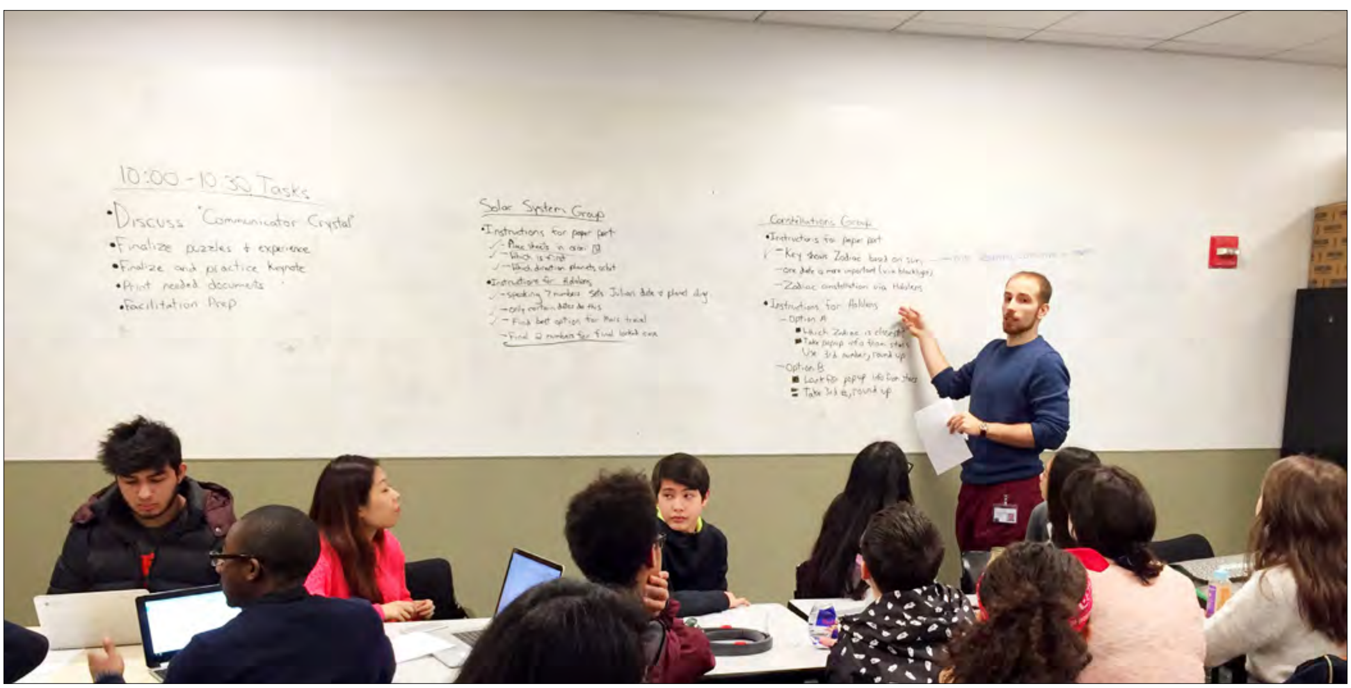

FIGURE 3. One instructor going through a design checklist. Photo credit: American Museum of Natural History

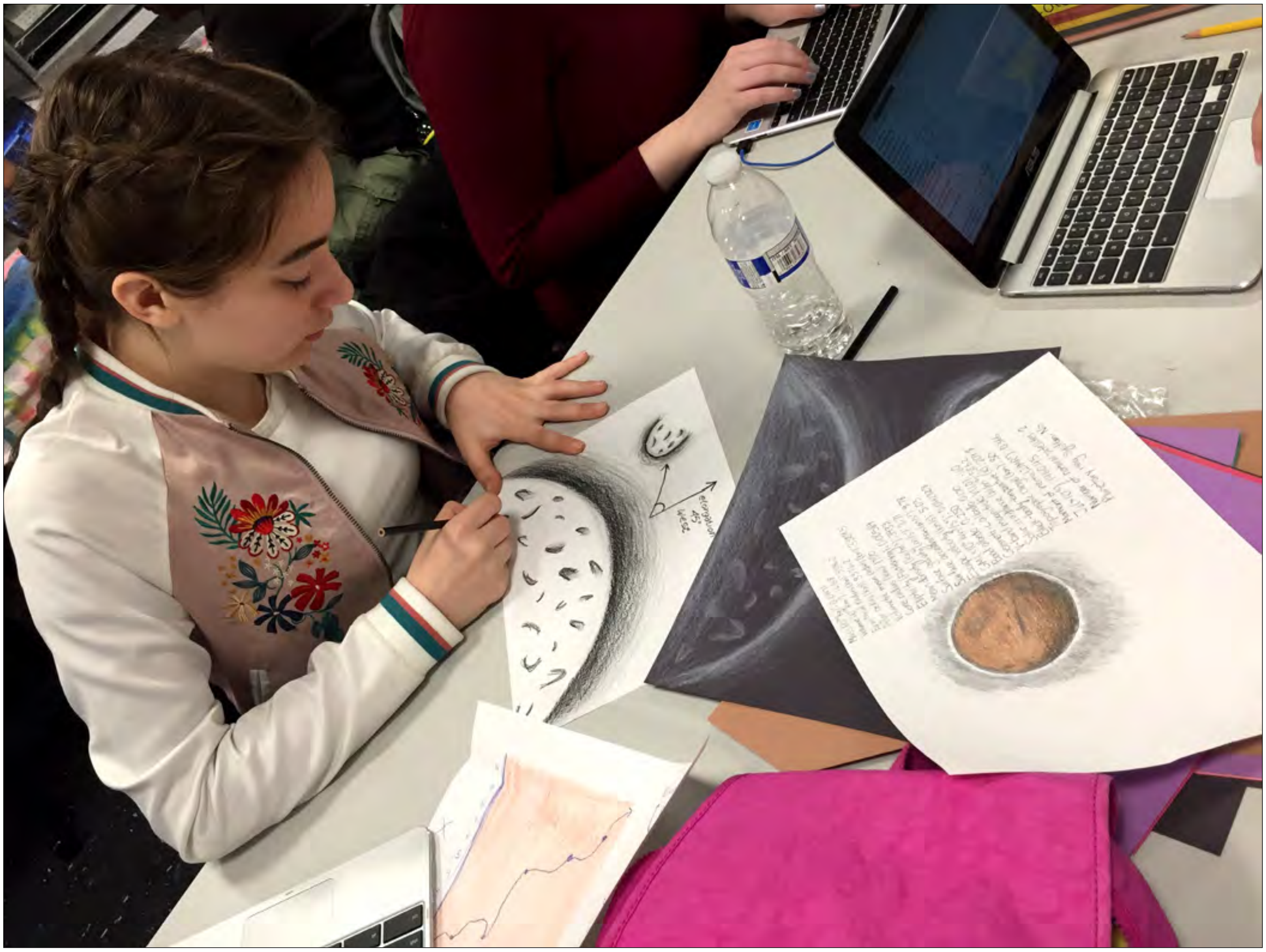

FIGURE 4. Student working on AR markers and props. Photo credit: American Museum of Natural History.

asked if the AR devices would be able to provide those visualizations. Because of this input, the students had everything they needed to design the two puzzles. One would focus on identifying a star within a constellation, and the other was to decipher the Julian date by looking at four different solar system pictures. It was advised to eventually use the available HoloLenses in each puzzle to view interactable clues as participants progressed through the game.

With a core concept in place, students broke out into their groups to build the experience. Puzzle groups were again rotated into using the AR devices to address any more necessary adjustments, while the layout and narrative groups worked on AR markers (e.g., images, drawings, etc.) to be arranged in the escape room environment (see Figure 4). These markers would then be picked up by the HoloLens to trigger the virtual starfield and map simulations for viewers. Other students worked on building for the remainder of the morning session in preparation for a mock-up presentation in the afternoon.

During the afternoon session, the class traveled back to the Black Hole Theater to prepare their mock run-through (see Figure 5). Students busied themselves around the room, discussing where clues, props, and puzzles should go, as well as how participants will access the HoloLens devices. The connection between the physical room setting and the simulations was the most interesting challenge for the students.

One initial idea was to make certain clues in the environment act as markers for the AR devices. A marker is a set location where a simulation could be activated and viewed. However, while working with the digital artist, this plan was deemed infeasible due to time constraints. Instead, the students decided to place the HoloLens devices in lockboxes at predetermined locations. The location of the lockbox for each HoloLens would instead act as the marker and the simulations would be viewable in those locations. The HoloLens lockboxes were then incorporated as a necessary step to solving their respective puzzles.

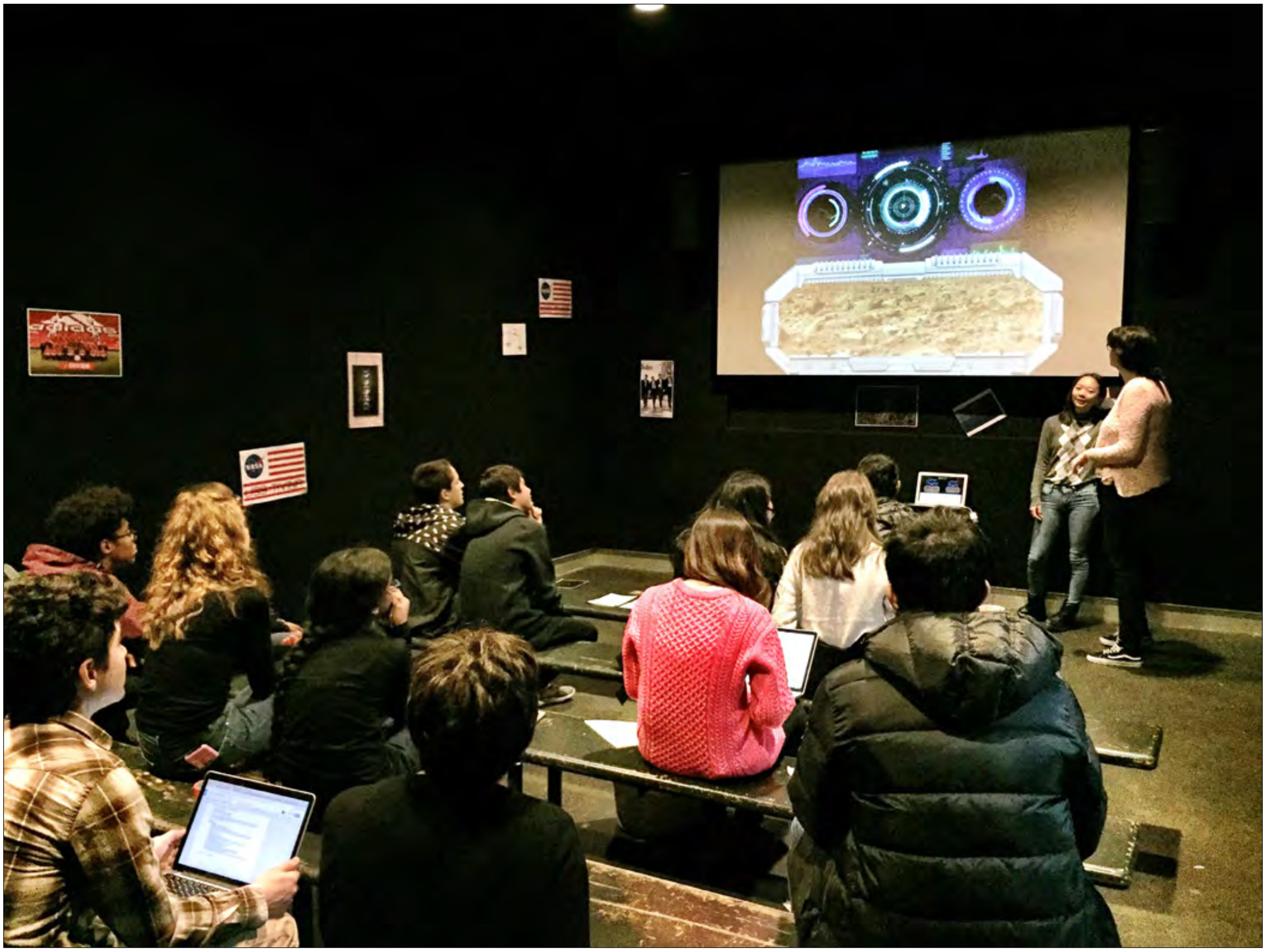

FIGURE 5. Students working through the mock trial run. Photo credit: American Museum of Natural History.

The original markers (e.g., printed constellations, maps, and charts) would match the locations of the corresponding virtual constellations but would become simple puzzle clues. This alteration would make it easier for participants to solve the puzzles, as they would only need to navigate around the room to see the simulations from different angles and use the physical clues to progress. The narrative group also created a quick draft of the introduction and closing scripts to be played on the theater's loudspeakers at the beginning and end of the escape room.

Running through the mock-up helped students identify any remaining issues they needed to address before the playtests on the following day. It gave them a sense of how the experience actually functioned and helped ease any uncertainty about their progress. At this point, only minor adjustments were needed before everything was ready for the playtest. Students worked for the remainder of the afternoon, finalizing all of the required assets. Puzzle groups also worked one more time with the digital artist to submit any final modifications for the simulations.

Course Design: Day Four

On the final day, students completed any necessary modifications to their vision for the *Escape the Planet!* experience. This included parallel puzzle solving for more seamless progression, implementing an end state when participants win or lose, and using student facilitators who can help provide hints or answer questions about the experience. Parallel puzzle-solving meant that puzzles could be solved independently rather than one leading into the next. Students also spent more time finishing their assets and puzzles, creating print instructions, drawing art for the walls, and recording audio for the introduction and conclusion.

During the afternoon session, two playtests were administered to provide students with feedback on their work. The first playtest consisted of AMNH staff, outside science experts, and an escape room designer (see Figure 6). This group was asked to give targeted feedback on (1) the accuracy of the science content embedded in the experience, (2) how well the instructional content (e.g., orbits, solar systems, etc.) was scaffolded as participants completed the challenges, (3) the effectiveness of the HoloLens simulations as both educational and engaging, and (4) if the escape room mechanics translated into an effective learning environment.

Shortly after the reviewers completed their run and provided their critiques, the room was reset for the second playtest consisting of a small high school class and their parents. One final debrief session occurred at the end of class so our students could digest the feedback they received, reflect on the challenges and successes in designing the experience, and their recommendations for the future iterations of their work.

Additionally, students were encouraged to speak candidly about their overall experience in leading a design project, the effectiveness of designing such a project in an educational environment, and to cite specific examples of their contributions to the project.

DESIGN CONSTRAINTS, ISSUES, AND REVELATIONS

The experimental *Escape the Planet* course revealed three major design issues; (a) challenges of class pacing and design time requirements, (b) the educational benefit of using an AR device was uncertain, and (c) modifying the AR simulations. We also uncovered two notable revelations; (a) student ownership of the design process, (b) meaningful student contributions and their engagement, and (c) designing the escape room supports knowledge construction.

Design Constraints

The course design of the *Escape the Planet* curriculum was largely impacted by the availability of prospective students and museum educational resources for experimental coursework. While we believed that four days would be sufficient to meet our learning goals and course objectives, we still had to streamline learning content in favor of more design time.

As such, only content related to solar systems and constellations was selected due to their importance in astronomy education. Because we wanted students to make a majority of the design decisions pertaining to the escape room (e.g., narrative, embedding HoloLens, and facilitation), the remaining class time had to be dedicated to building and testing. To help alleviate management challenges due to the expedited schedule, we ensured that other facilitators (e.g., teaching assistants, digital artist, etc.) were present to assist as needed.

FIGURE 6. First playtest with educators, science experts, and designers. Photo credit: American Museum of Natural History and Denis Finnin.

HoloLens Constraints

One of the main limitations of the HoloLens was the programming experience required to create virtual simulations in Unity to upload onto the devices. Because of this, students could only work with the pre-generated simulations that we created and could not modify them or their implementation in the escape room. We addressed this constraint by ensuring students worked closely with the digital artist. While they could not edit the simulations directly, students were not that disconnected from the HoloLens design process. As a result, students could still make recommendations that would adjust their use considerably and still fulfill their designer role without additional responsibilities. However, working with a digital artist with *Unity* experience may not be feasible for other institutions.

Another limitation of the HoloLens technology is the time requirement needed to introduce the device to prospective users, as they must first go through a 5-10 minute tutorial to learn the nuances of using the device. While a simple exercise for an individual at home, facilitating the process for 17 students would take time. We accounted for this by dedicating an afternoon session and rotating small groups of students into learning the HoloLens, but that time was precious.

We also anticipated that this tutorial process would not be feasible during the playtests. To compensate, we urged students to work with the digital artist to strip any type of interactivity unique to the HoloLens that had a learning curve. Based on recommendations from the students, participants would be limited to looking around, moving to adjust their perspective, and giving voice commands while using the devices. In essence, they would be able to simply pick up the devices and use them intuitively without assistance.

Design Issues

Length of Class and Pacing

Given the objectives of the course, we believed that four days would be sufficient to teach students two astronomy topics (i.e., solar systems and constellations), understand Digital Universe datasets via *Uniview*, and to create a student-design escape room with embedded AR simulations. While we anticipated students would need multiple design sessions and reflection exercises to assess their understanding of the content, we did not expect the amount of time students would need to establish a workable prototype.

As a result, the rigidity of the course schedule compromised the depth of instructional content students received during class sessions. For example, one of the main learning goals for the course was to teach students data visualization and how to work with the Digital Universe datasets via the *Uniview* program. While students did have time to use the program, time requirements prevented us from pairing this experience with the HoloLens simulations we created for the course. We felt that the additional time was better spent on students designing the escape room.

Despite our emphasis on scheduling as much design time as possible, every moment of it was precious. While we achieved our goal of working with students to co-develop the prototype, the expediency of the class schedule hamstrung our ability to cover everything we wanted. While four days is sufficient for students to design a playable escape room prototype, the cost of losing additional astronomy content and connective activities using the available technology was apparent.

Uncertain Educational Benefit of the HoloLens

It was an enticing prospect to use a HoloLens in an educational escape room experience that connected with science content via interactive puzzles. As expected, student and playtest participant engagement was incredibly high. However, their educational benefit in a classroom remains uncertain. This is simply because we did not use the HoloLens to teach our students astronomy content, or have in-class instructional activities that required their use. Rather, students helped embed instructional content into the simulations to teach participants as they completed the puzzles.

For example, the constellations puzzle simulation required the player to understand that stars reside in a 3D space. They then had to use that knowledge to find the star closest to their location and then pull information from its Z axis to complete the puzzle. Also, because the solar system simulation took longer to implement into the escape room than planned, the experience was stripped down to not require science knowledge to complete.

In addition, as mentioned previously, we did not have the opportunity to use the HoloLens to solidify student understanding of data visualization and solar system properties. This is not to say that students cannot learn science topics from using an AR device like the HoloLens, only that we did not use them with our students for this particular purpose.

Modifying the AR Simulations

During design sessions after the first day, each student group needed to work closely with the digital artist to best incorporate the HoloLens into the escape room. Because of the time and programming knowledge needed to develop or modify the virtual simulations, students could only make recommendations on their design and usage.

As a result, any necessary changes were completed after hours by the digital artist in preparation for the following day. However, due to how we scheduled the class, there was realistically only one day available to make any significant alterations. This was because the class was designed to put students in the driver's seat as designers, and a majority of the final decisions pertaining to the HoloLens were made at the conclusion of the second day. This occurred when the project's scope and narrative were finalized after the pitch to Science Bulletins.

Regardless, the digital artist frequently worked beyond midnight to make any changes as needed. Coupled with the difficulty of producing interactive simulations for the HoloLens, as well as making additional changes based on student feedback during class, more constraints were needed to reduce production time and in-class facilitation to better utilize the technology's affordances. This may have also saved time for other elements of designing the escape room or for additional sessions dedicated to teaching astronomy content.

Many institutions may not have access to a staff member versed in *Unity* or programming. This means that resources are spent for outside expertise, or comparable AR apps must be located online. This represents a core issue in using such technology in classrooms. The available ecosystem is a difficult constraint to navigate and more accessible alternatives would undoubtedly be prioritized.

Design Revelations

Students as Designers

As the course progressed and students worked on their escape room projects, we had to adjust the ways we facilitated the design process so students could confidently embrace their roles as designers. For example, when students began designing the escape room experience they often began statements with phrases such as "Can we…" or "Is it okay to…" In essence, they were asking educators for permission to craft the experience in particular ways (e.g., astronomy topic, puzzle mechanics, AR, etc.).

In response to this behavior, we incorporated targeted reflection questions into our student-design framework that focused on their team roles and design processes. Specifically, we phrased questions to include prompts such as, "What were your decisions…," "How did you address…,"

FIGURE 7. Student designers working together while using the HoloLens. Photo credit: American Museum of Natural History.

and “What do you recommend…” In addition, educators patrolled the class and worked with student groups to further reinforce this mindset by pushing them to make tough decisions and address playtester feedback. Our goal was to train students to think like designers, have confidence in their decisions, and help establish a sense of ownership over the project (see Figure 7).

As a result of these adjustments, student behaviors indicated notable degrees of ownership over their work. They began using the educators as resources and collaborators, rather than a source for direction or authority (see Figure 8). This was further evidenced on day three when students made the decision to redesign the escape room’s puzzle progression. Specifically, there was a debate between the student groups if both HoloLens-based puzzles should be solved in parallel, or have participants complete them sequentially to reduce cognitive load.

Based on recommendations (not demands) from the teachers, students broke down aspects of each puzzle to find that there was no logical sequence to them. Instead, they felt that parallel puzzle progression would be the preferred option. This wasn’t a conclusion that we gave them, they simply discovered this for themselves. We believe that the designer identity we helped support enabled students to confidently explore this challenge and address it in a manner of their choosing.

Meaningful Contributions

During debrief exercises focusing on the design sessions and playtests, a majority of students gave examples of contributions they made that were implemented into the final prototype (e.g., written instructions, narrative, props). Additionally, students could also explain why other ideas did not make the cut or provided a clear reasoning for why particular ideas were altered (e.g., lack of resources, fun factor, and balance).

They understood that this was a normal part of the iterative process. More importantly, when asked who contributed the majority of ideas for the final escape prototype, half responded that it was an equal combination of students and staff, while the other said it was the students themselves. In essence, they felt in control, believed the project implemented their ideas, and it was a collaborative project with the educators. Specific responses include, “...I was really thrilled to watch others enjoy one that I helped to create...” and “It was very rewarding [to work with others], and I felt a strong sense of pride in the team’s work...” Students focused considerable time on developing the escape room, and their engagement further exemplifies their dedication to the design process.

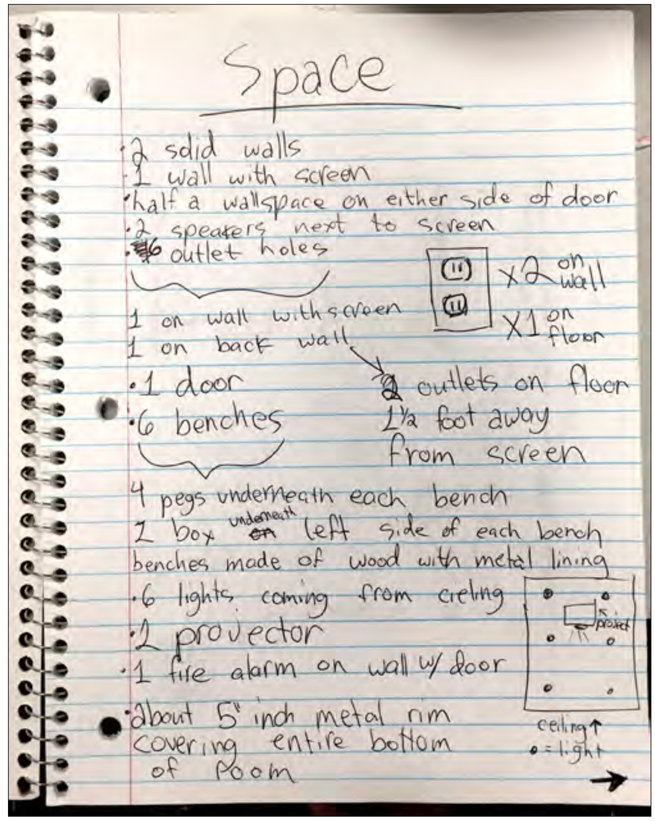

FIGURE 8. Student designer checklist and notes. Photo credit: American Museum of Natural History.

Escape Room Supports Knowledge Construction

By working with students to embed accurate science content into the escape room, students were able to transfer their understanding of solar systems and constellations into a gamified context. This process offered students a unique way of applying their knowledge of astronomy into an interactive experience. Additionally, because the escape room was also designed to be educational, students not only had to approach the project as designers but as teachers as well. They had to consider prior knowledge, participant age, and education level in ways that influence the breadth of the instructional content they were building into the experience.

Pairing the escape room with the HoloLens astronomy simulations also encouraged students to address the impact the technology had on the learning process. They navigated issues of cognitive load and strategized on ways the instructional content could be leveraged with the devices. Reflection and debrief exercises also helped probe student knowledge and solidify their understanding of the learning content. As a result, students were diligent in ensuring the accuracy and clarity of the science content in the game. To that end, designing the escape room experience gave students the experience to scaffold astronomy content into a digestible experience that was educational to multiple audiences.

FUTURE DEVELOPMENTS OF THE DESIGN

The American Museum of Natural History's science-based curriculum paired augmented reality with a student-designed escape room experience. The goal of this experimental coursework was to ascertain the positive effects of teaching science with a student-designed escape room supported by augmented reality. If there was enough interest in the program, this escape room would then be transformed into an actual exhibit.

We believe situating students as designers, and giving them control over a project, offering them a unique opportunity to apply their understanding of astronomy and make considerations when educating others. As designers, students had to work with incomplete knowledge, test and retest design ideas, and modify and reflect on failed attempts. These experiences are embedded in the daily experiences of both scientists and designers.

However, a student-designer framework is not without its limitations. As described in the design issues section, we faced the challenge of balancing desired outcomes (e.g., functional escape room experience) with class time constraints. Furthermore, as educators with a wide range of technological devices at our disposal, we became overly ambitious with how much we tried to embed in such a short course. As such, we believe additional class days are needed to allow students sufficient time to acquire a deeper understanding of astronomy concepts, have more targeted reflection exercises that focused on student learning, and the time needed to create a fully functional escape room experience rather than a playable prototype. More time would also mean a stronger implementation of the HoloLenses as learning tools.

Future designs could also focus on further developing our framework. While for this class, we asked students to design an escape room experience using their astronomy knowledge, other courses could implement different content areas (e.g., math, reading) to recreate a similar context for students.

We believe positioning students as designers and educators as collaborators offered a unique insight into how students solve problems, embody the role of a designer, and create a playable prototype for education. As educators, we were surprised at some of the paths students took to reach their final designs, and these insights offered us new ways to better understand how students learn.

This was particularly apparent when student groups debated on cutting particular parts of the experience (e.g., AR interactivity in favor of accessibility), or adjusting mechanics (e.g., puzzle progression, science content, instructions, etc.) to enhance the educational affordances of the experience. Future designs can better embed scenarios that encourage students to address design problems as approaches to promote scientific thinking and learning transferable skills.

Our course may also benefit from fewer technological options. As mentioned, we used both *Uniview* and the HoloLens. This conclusion stemmed from our observations of students who are working on connecting the HoloLens simulations with escape room puzzles. We believe that they were not fully interacting with the devices for the purposes of learning astronomy.

In essence, they did not see the HoloLens simulations as engaging, contextual learning experiences to explore science content, but merely as tools to leverage during the design process. However, this was not the fault of the students, as we facilitated the course to use the AR devices in this manner. Future iterations of our design would revise how the HoloLens is utilized and better consider the prospective educational benefits of the devices for our students.

Lastly, it is worth considering that students be required to maintain a design journal where they record and reflect on the challenges and opportunities they experienced with the *Escape the Planet* course. We could refer to their journals as a way to recall previous experiences and further improve their scientific understanding. This tool could serve as a way for students to recall key points within the course to reflect on the insights they learned to grow and improve. This addition could offer another approach for students to focus on the science content of the course and may serve as an inspiration for their future inquiry and science exploration.

CONCLUSION: USING A STUDENT-DESIGN TASK TO SUPPORT SCIENCE LEARNING

In this paper, we presented a science-based curriculum with a student-designed escape room experience. Designing an escape room experience provided students with an exciting opportunity to apply their understanding of astronomy concepts. We presented how our course prepared students to apply science learning in their design process. We also described our role as educators and how we transitioned into student collaborators while students designed the escape room experience and connected astronomy activities.

We also discussed how we used embedded AR via the HoloLens in the escape room and offered students different technological tools for use in their designs. Although the student-as-designer framework offered a unique opportunity for students, we did experience some unexpected issues (e.g., time constraints and underused technology). Lastly, we reflected on how we sought to improve our design and present future directions for this work. We have drawn upon the engaging aspects of collaborative learning and design-based activities to help foster student creativity, learning, and confidence in their work. We believe we provided our students with an indelible and effective learning experience.

ACKNOWLEDGMENTS

We would like to thank the American Museum of Natural History, the Youth Initiatives Program, and Science Bulletins for making this experimental course possible. We also thank Barry Joseph for spearheading the project and providing students with great ideas and feedback on their work. Thanks go to Evan Ramm for being the astronomy guru and helping students connect science to their designs. We also thank Eojin Chae for her HoloLens and Unity expertise and for designing the simulations and working with the students. We thank Hannah Jaris for her support, feedback, and facilitation. Above all, our gratitude goes to our wonderful group of dedicated students for their hard work, diligence, and understanding in helping our class and the escape room be the best they could be! We wish you the best of luck in your future scholastic endeavors!

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