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Augmented Reality Plant & Animal Cells: Design and Evaluation of an Educational Augmented Reality Application

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Abstract

In this paper, we present a usability evaluation of a custom AR educational tool designed to improve students' understanding of the similarities and differences between plant and animal cells. We argue that the design of the Augmented Reality Plant & Animal Cells (ARPAC) tool promotes a self-driven approach to learning by presenting textbook content as interactive, 3D models that can be uncovered by exploring sections of their school textbooks with our app. Furthermore, the design of ARPAC can be mapped easily onto other subjects, providing teachers with additional pedagogical tools to utilize in the classroom. Preliminary results of a usability study support our initial design of a textbook-driven AR application to support learning in science subjects.

1. Introduction

As an emerging technology, Augmented Reality (AR) has the potential to improve engagement in classrooms by bridging the gap between tangible pedagogical tools and abstract educational concepts (Billinghurst & Duenser, 2012; Cooper, Cooper, Bauder, & Simmons, 2019; Yip, Wong, Yick, Chan, & Wong, 2019). AR mixes virtual and real elements by presenting an interactive experience where real-world environments are "augmented" with computer-generated information. More and more classrooms in North America have incorporated digital technologies such as tablets and smartboards – however, they continue to rely heavily on textbooks for teaching purposes (Mayfield et al., 2019). Although numerous studies have indicated that AR promotes enhanced learning (Abbasi, Waseem, & Ashraf, 2017; Akçayır & € Okçe Akçayır, 2017; Amaia, Inigo, Jorge, & Enara, 2016; Billinghurst & Duenser, 2012; Bratitsis, Bardanika, & Ioannou, 2017; Chen, Ho, & Lin, 2015; Li, van der Spek, Hu, & Feijs, 2017; Martinez, Benito, Gonzalez, & Ajuria, 2017; Umer, Nasir, Khan, Ali, & Ahmed, 2017), many educational AR applications suffer from usability issues, especially when their design does not account for the physical and cognitive skills of the target age group (Radu, MacIntyre, & Lourenco, 2016). Researchers have explored educational AR applications to help children learn mathematics and science literacy (Dunleavy, Dede, & Mitchell, 2009), teaching geometric shapes to preschool children (Gecu-Parmaksiz & Delialioglu, 2019), and even to support young students with autism spectrum disorder (ASD) (Lumbreras & Ariel, 2018) and Dyscalculia (Avila-Pesantes et al., 2018). Common challenges include physical, cognitive, and socio-emotional development, motor abilities, spatial cognition, attention, logic and memory, and other disability issues (Radu & MacIntyre, 2012; Lin et al., 2018). While we acknowledge the importance of cognitive and physical skills in designing AR applications for young learners, this was not the focus of this study. However, we plan to explore these issues via future work.

Science teachers face numerous challenges teaching scientific concepts to elementary school students. For example, Chavan reports that teachers face challenges in helping students grasp biology concepts such as cell structure, segmentation, asexual reproduction (Chavan, 2016). Furthermore, Chavan notes science teachers surveyed have expressed a desire to incorporate more interactive learning aids to provide for a more immersive learning experience for 21st-century learners. Researchers and educators have looked to serious games as one possible avenue to motivate today's learners (Malliarakis, Satratzemi, & Xinogalos, 2014; Mayfield et al., 2019).

Researchers have also studied AR as a potential educational tool (Abbasi et al., 2017; Akçayır & € Okçe Akçayır, 2017; Amaia et al., 2016; Billinghurst & Duenser, 2012; Bratitsis et al., 2017; Chen et al., 2015; Li et al., 2017; Martinez et al., 2017; Umer et al., 2017). One popular stance on educational AR is that the best approach is one that integrates AR with existing teaching methods (Abbasi et al., 2017; Bratitsis et al., 2017; Chen et al., 2015; Kundu, Muhammad, & Sattar, 2017; Qiwen & Yongming, 2017; Umer et al., 2017). To this end, we developed an AR educational tool that maps educational content onto textbooks that are already being used by students in the classroom. We argue that this approach makes it easier for teachers to integrate AR educational tools into their lesson plans. Here, we describe the first phase of this study, in which we focused on the usability of the application itself. We argue that linking 3D interactive models to existing textbook material promotes a sense of curiosity and discovery in which students are motivated to evaluate their knowledge of plant and animal cell structures.

2. Related Work

2.1. Technology in Education

In our increasingly technological world, researchers and educators have struggled to find new and innovative ways to promote STEM (science, technology, engineering, and math) subjects to prepare students to live and work in the 21st century. Educators in Canada continue to struggle with identifying new and innovative ways to encourage STEM within their classrooms while managing a large group of diverse learners and keeping within curricular requirements. In a recent report, researchers identified a number of issues with science education in North America, including a disparity between current pedagogical research and curricular policy (Olson, Tippett, Milford, Ohana, & Clough, 2015).

Although technology is becoming more prevalent in the classroom, another issue barring teachers from effectively using novel pedagogical technologies is that many are not aware of the different kinds of applications that are available to them. For example, a paper by Kiat et al. (2016) compares the three types of technology AR, Virtual Learning Environments (VLE), and Mobile Learning. The study gives a detailed overview of each technology and describes how it can be implemented in the classroom. The authors note that the aforementioned technologies may not be suitable to all subjects, and thus, a degree of familiarity with the technologies and curricula is necessary to ensure successful integration (Kiat, Ali, Halim, & Ibrahim, 2016). Here, we propose that a tool designed to work with existing textbooks is ideal, as it would provide a more seamless approach to combining interactive digital content with traditional pedagogical tools.

2.2. Educational AR Applications

Akçayır and Akçayır present a survey of 68 studies exploring AR as a pedagogical tool, noting an increase in the number of AR studies in the last four years. The advantages of AR include enhanced learner outcomes, contributions to pedagogy, and increased interactions (student-student, student-material, and student-teacher). However, the authors note that most of the papers included in the survey reported on first-time use of AR in each of the classrooms studied, suggesting that there could be a novelty effect that may diminish over time. Furthermore, the authors note that usability issues and regular technical problems remain challenges in educational AR (Akçayır & € Okçe Akçayır, 2017).

In another paper, Billinghurst and Dünser discuss the usability of AR in the classroom. Specifically, the authors ask whether or not AR enhances elementary and high school education, and if so, what are the specific affordances of AR that make it an effective pedagogical tool? To answer these questions, they developed two AR learning formats: AR books and AR applications for their handheld devices. Based on their results, the authors suggest blending AR with traditional learning. However, they note that technological barriers, such as limited programming and 3D modeling skills, make it difficult for teachers to develop their own AR educational content (Billinghurst & Duenser, 2012).

In addition to STEM subjects, AR applications can also be leveraged to support learning in language classrooms. McArthur (2019) designed an AR language application to teach the meanings of kanji (Japanese logocentric letters) to students learning the Japanese language. Students view cue cards through a mobile camera, triggering an animation that reveals the meaning of the character and its relationship to the shape of the letter itself. Amaia et al. designed and evaluated an AR application aimed at improving students' knowledge of vocabulary and grammar in English while introducing curricular content of emotional intelligence in a CLIL approach. In addition to design considerations, the authors also note that noise in the classroom is a factor that can potentially impact learning applications that require listening (Martinez et al., 2017). The authors report on a second AR application: LEIHOA, a system designed to help young children learn numbers in a second language. Leveraging the affordances of AR, LEIHOA offers interactivity and uses visual, auditory and tactile stimuli to provides engaging opportunities for developing attention while learning new concepts. Although the paper does not provide a formal evaluation or analysis for this project, it is one of a few papers that explores educational AR for use in preschool settings (Amaia et al., 2016).

A number of researchers have explored AR tools to promote learning in STEM subjects, such as 3D shapes (Kouzi & Shafiq, 2019), marine life (Chen et al., 2015), the water cycle (Bratitsis et al., 2017), plants (Umer et al., 2017), chemistry (Abbasi et al., 2017), and geoscience (Kundu et al., 2017). These applications have been explored in primary [e.g., see: (Bratitsis et al., 2017; Chen et al., 2015; Kouzi & Shafiq, 2019)] and secondary [e.g., see: (Umer et al., 2017)] classrooms. For example, Bratitsis et al. report on an educational AR application designed to support students learning about the water cycle in elementary classrooms. The authors note that the AR application helped students develop a visual relationship to the water cycle. Specifically, the AR visualization helped students understand that water is not vanishing, but it is being recycled, following certain stages. AR can also be leveraged to support inquiry-based learning in the science classroom. For example, Ahmed et al. report on MAPILS (Mobile Augmented Reality Plant Inquiry Learning System), an AR application designed to support students learning about plants in secondary schools (Umer et al., 2017). A qualitative evaluation revealed that, although the application did engage students, there were some usability concerns, and some students reported that they lost interest over time due to a lack of gamified elements in the application.

Nearly all of the aforementioned examples use marker-based AR (AR that links virtual content to pictures or markers); however, Kundu et al. report on a tactile AR application using a physical sandbox. The application uses AR software, a Kinect sensor, and a projector that detects sand topology in real-time and projects diverse types of terrain on it. This AR sandbox is a critical hands-on learning tool that helps improve students' understanding of fundamental concepts of Geoscience (Kundu et al., 2017).

As we look to the future of AR educational applications, ongoing increases in computing power could soon offer novel applications resulting in self-adaptive global structures that could connect countless students in collaborative augmented environments, where user performance could be evaluated in real-time. New technologies might afford the creation of user-tailored pedagogical activities, where students might follow a personalized curriculum modified to their educational skills (Qiwen & Yongming, 2017).

2.3. Gap Analysis

In our review of the literature presenting STEM-based AR applications, we noted a lack in applications that teach the differences and similarities between plant and animal cells. To this end, we developed ARPAC to help students create a meaningful relationship to this knowledge through an interactive AR application that is linked to their textbooks. In this study, we present a preliminary usability analysis of this application using heuristics presented in the PREMEGA framework (Shoukry, Sturm, & Galal-Edeen, 2015).

The ARPAC application takes the cells out of a two-dimensional textbook and presents it to students as a complete three-dimensional model placed in front of them. Using the application, which runs on a smartphone or tablet, students can develop a visual understanding of plant and animal cells by tilting, rotating, and panning the camera around the 3D virtual content. Furthermore, the application presents students with interactive virtual buttons that allow them to access targeted content as needed. This is a novel application for several reasons:

- To the best of our knowledge, this is the first Augmented Reality application to visualize plant and animal cells. This exploration enables students to explore the similarities and differences of those cells via interactive textual annotation describing the cell structures.
- This application is easy to use. Fewer interruptions due to usability issues result in a more engaging learning experience.
- The markers of this application are intentionally made simple so that the participants will expect what to see as AR above each figure.
- The presence of the virtual button allows participants to access additional information on demand.

3. The Application

The development tools that have been used for this application are Unity editor 2017.3.1 and Vuforia Software Development Kit (SDK) for Android. The Android SDK is also required for compilation. The Unity engine supports the development of applications for PC, Android, and IOS using the Unity graphics engine. Vuforia is an Augmented Reality SDK for mobile devices that uses computer vision to recognize markers, allowing developers to link virtual content (e.g., pictures, movies, 3D models, audio files, etc.) to real-world objects. The Vuforia SDK is available for Android Studio, XCode, and Unity, which was selected for this application.

The application was developed to recognize a specific cell diagram as a marker Figure 1 so that it can display the 3D model on top of it. The 3D model consists of two 3D cells next to each other, giving the participant the chance to view the similarities between the two cells and study the differences between them. The participant opens the application using their Tablet, and then they look through the Tablet's camera at the marker on the page. Viewing the marker triggers the AR content – when the camera sees the marker, it displays the 3D models floating just above the picture. The image consists of two 3D cells next to each other. The students can rotate the paper to view the 3D models from different angles.

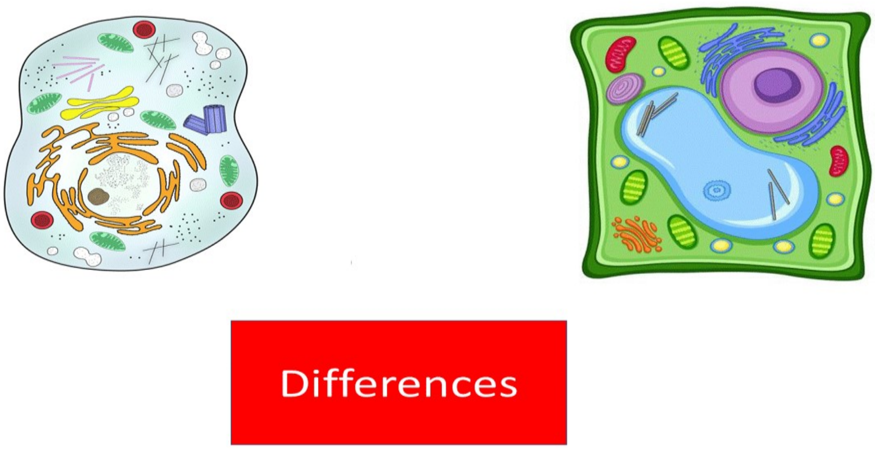

Figure 1: ARPAC marker

As noted previously, a virtual button in the application allows users to access additional information about the models. Figure 2 shows the workflow of the application.

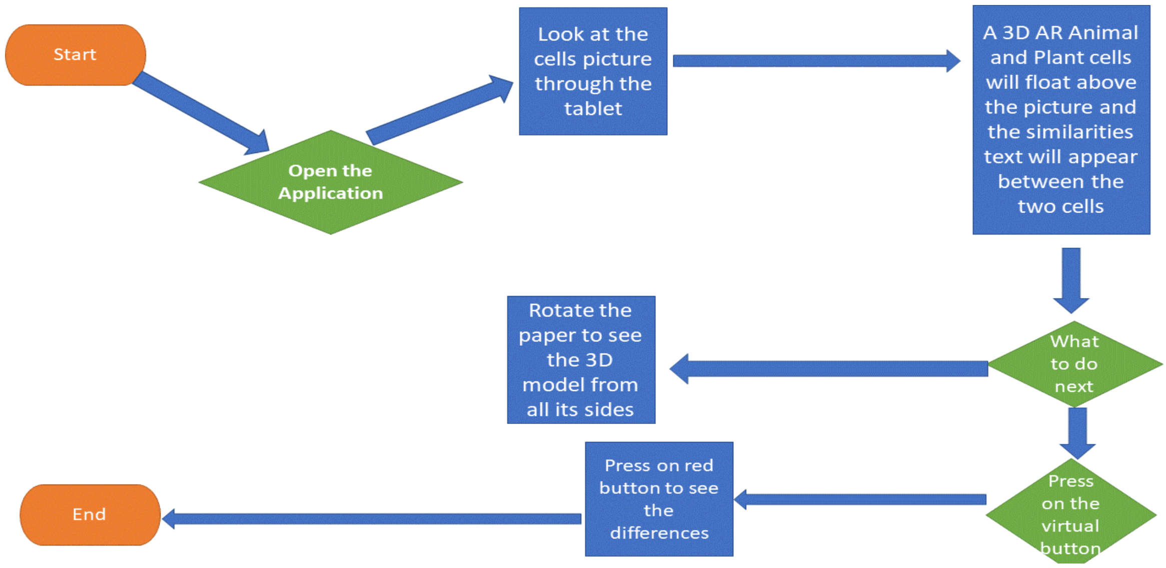

Figure 2: The Application Work Flow

A C# script is attached to each virtual button. The following is a Pseudo Code for the virtual button code file:

1. When pressed on Virtual Button of differences
   1.1. Show Differences
   1.2. Keep it active while still pressed
2. When released the Virtual Button
   2.1. Hide the Differences

Figure 3: ARPAC Application

4. Methodology

The goal of this project is to support learning in the classroom by developing AR technology that maps interactive content directly onto textbooks that have already been selected by the teacher to support the curriculum. Our motivation is to demonstrate that the effect of this kind of integration has demonstrable benefits to learning beyond novelty effects and can increase their understanding of complex STEM subjects. In this paper, we present our initial usability study of an application designed to support one unit in a Biology course. As noted in related work, usability issues were cited as having a significant impact on the effectiveness of educational AR applications (Akçayır & € Okçe Akçayır, 2017) (Radu et al., 2016). As such, this paper is primarily focused on the initial usability evaluation of the application. However, in future work, we intend to study the application in classrooms in order to better understand usability concerns with the target user group in addition to assessing the application's potential to support learning. In our evaluation, we utilized components of Shoukry et al.'s PreMEGA framework, which provides detailed heuristics for the evaluation of mobile pedagogical technologies developed for children (Shoukry et al., 2015). Although many heuristics pertaining to game mechanics and avatars were not applicable here, those relevant to issues of usability, interactivity, and pedagogical content design were most useful and informed the design of our usability questionnaire.

4.1. Participants

Participants for this study were recruited from Carleton University in Ottawa, Canada, using convenience sampling. The selected user sample aligns with other usability studies in the field of human-computer interaction (HCI) that conduct preliminary usability analyses with a more convenient population (Sakamaki et al., 2018). Participants were all current students at the university. In total, 15 participants took part in this study, including eight women (mean age = 30) and seven men (mean age = 35). Nine participants had a Bachelor's degree, seven had completed Grade 12, and two had a master's degree. One participant chose to omit this information on the questionnaire. Although the application is designed for elementary school students, the purpose of this study was primarily to assess the usability of the application in order to address any significant design problems before launching the application in classrooms. The participants are adults, and we assume that they have a general knowledge about the subject matter covered by the application. However, as we were not assessing learning effects in this study, familiarity with the subject matter was not required to participate in this study. Thus, although our participants do not represent the target group for the content of the educational application, we are satisfied with their data as a benchmark for overall usability.

4.2. Procedure

Following an intake survey, participants started the application and were encouraged to freely explore the application for five minutes. Researchers took detailed observational notes for each session and coded these notes using qualitative analysis software. At the conclusion of the study, participants were given a sheet containing demographic questions, questions designed to collect data on their familiarity with mobile and AR technologies, and Likert scale questions designed to assess the usability of the application. These questions were derived from the PreMEGA Framework (Shoukry et al., 2015). Survey and questionnaire data were entered into Excel and coded by the research team for analysis. The results are presented in the following section.

5. Results

5.1. Results from the Questionnaire

Following demographic information (reported above in the Participants section), participants answered a series of questions designed to ascertain their familiarity with mobile and AR technologies. These questions were included in order to rule out any confounding variables. Overall, participants reported an above-average familiarity with these technologies. Most of our participants (73%) were very comfortable using mobile technologies, where 20% were comfortable, and only 7% indicated that their comfort with mobile technologies was natural but not exceptional.

Our next questions pertained to the overall design of the application as well as participants' perceptions about the effectiveness of AR as an educational tool. When asked to reflect on their overall experience using the application, feedback was quite positive (*mean* = 4.33, *st dev* = 0.72). As for their opinions regarding the potential effectiveness of AR as a pedagogical tool, results indicate that our participants feel as though AR is an effective educational technology (*mean* = 4.6, *st dev* = 0.63).

When asked to reflect on the design of the application, participants commented that they liked how detailed the 3D models were, that the interactivity of the application helped to facilitate the learning process and that the interactive features were responsive and intuitive. They also commented on the visual presentation of the educational content, noting that the figures were precise and easy to understand.

In addition to this feedback, participants also provided constructive criticism on the design of the application including issues with the font size in the AR text, some fatigue when holding the device over the marker for extended periods of time, and some awkwardness in holding the device in one hand while accessing virtual buttons with the other. Some participants indicated that it would be better if we provided a description next to each cell.

5.2. Heuristic Evaluation

Next, mobilizing heuristics from the PreMEGA framework (Shoukry et al., 2015), we evaluated participant feedback on the usability of our application.

Efficiency:

- The application started quickly.
- The application enables independent use after first use.
- The application consistently responses to user actions.
- The application has clear, fun actions to reach educational goals.

Effectiveness:

- The application makes connections to learning contents.
- The application is supportive rather than distractive.
- The application show figures based on real-life experiences.
- The application uses a theme meaningful to children.
- Augmented Reality is a good tool to be used for educational games.

Satisfaction:

- I felt satisfied with the educational content found in this AR application.
- It was easy to understand the differences and similarities between the two cells in this application
- The elements of the application the interface was easy to identify.
- I felt comfortable to hold the device and press the virtual button.

5.2.1. Efficiency

We used the heuristics of the PreMEGA Framework to evaluate the efficiency of the application design. Heuristics were presented as positive statements on usability using a 5-point Likert scale where high values indicate agreement with the heuristic. Efficiency here refers to the overall responsiveness of the application (e.g., content loading time, response to user inputs, etc.). System efficiency relates not only to the computational power of the device running the application, but also coding choices that can impact system responsiveness and lag. Overall, ARPAC scored very well on efficiency heuristics. Participants indicated that the application started quickly (*mean* = 4.4, *st dev* = 0.74). Regarding User Interface (UI) design and ease of use, participants indicated that the application design enables independent use after first use (mean=4.6, *st dev* = 0.50). When asked about the consistency response to the user actions of the application, participants noticed that the application response well to user actions (*mean* = 4.4, *st dev* = 0.73).

Overall, participants indicated that the educational goals of the application were clear (*mean* = 4.6, *st dev* = 0.50). Participant feedback on the efficiency of the design was consistently high. We assert that these preliminary results reflect positively on the usability of this application for the intended educational purpose.

5.2.2. Effectiveness

Where efficiency heuristics are linked to general usability, effectiveness heuristics assess the ease of use of the application regarding the interactivity of educational content. We asked participants to reflect on whether the application makes a strong connection to learning content. Participant feedback on this heuristic was positive (mean = 4.7, *st dev* = 0.48). Most of the participants found the application supportive of learning goals rather than distractive (*mean* = 4.7, *st dev* = 0.62). The participants also evaluated the content delivery and presentation of the interactive 3D AR models as appropriate to the subject matter (*mean* = 4.4, *st dev* = 0.63). Participants also indicated that the application design seems meaningful for the target age group (*mean* = 4.5, *st dev* = 0.74).

The application will be considered effective if it has a high degree of success in increasing the learner's interest in the subject matter and if it provides a fun and engaging way to interact with educational content. Overall, 90% of our participants agree that the application is effective, which does reflect positively on the usability of this application for the intended educational purpose. We were further interested in learning whether or not our participants felt as though AR would be a useful pedagogical tool – beyond the initial novelty effect. Although the duration of the study does not allow us to accurately assess novelty effects, we note here that participants agreed that AR is a good tool to support traditional classroom teaching (*mean* = 4.3, *st dev* = 0.82).

5.2.3. Satisfaction

The final set of questions was used to assess the features that were unique to this application. Specifically, we were interested in whether or not the educational content of the application was easy to understand if the differences between the cell types were presented effectively, and how participants felt about the interactive content and virtual buttons. Overall, participants agreed that they were satisfied with the educational content of the application (*mean* = 4.5, *st dev* = 0.51). The participants also agreed that it was easy to understand the differences and similarities between the two types of cells presented in this application. None of the participants disagreed about the easiness of it. The results were (*mean* = 4.5, *st dev* = 0.51). The participants also noted that the elements of the application interface were easy to identify (*mean* = 4.4, *st dev* = 0.74).

This application required the user to hold the device and point it to the marker; then, the user has to press on the virtual button found on the marker (paper). Although participants indicated that they were comfortable viewing and interacting with the virtual button for the duration of the study (*mean* = 4.3, *st dev* = 0.8), some participants indicated some fatigue in performing this type of interaction over extended periods of time, which could introduce problems in-classroom use, where students would likely be using the application more frequently and for longer periods of time.

Overall, the results of our initial study on the usability of the application are quite promising. User feedback was overall quite high, and the design of the application seemed to spark our participants' interest in learning more about the subject matter. Using these results going forward, we plan to modify the application to take some of the usability concerns into account before launching a longitudinal study in our local schools. Also, we hypothesize that the design of ARPAC can be mapped easily onto other applications in biology topics, mathematics, chemistry, and visualizing physics in textbooks and circuits in which we can show the similarities and differences between two comparable items.

6. Conclusions, Limitations, and Future Work

Previous work shows that Augmented Reality can be effectively utilized in the classroom to increase learner motivation. In this paper, we presented PARAC, an AR educational application to promote STEM learning. Although the focus of this application was on a specific unit in Biology, we plan to explore other designs to generate a set of heuristics specific to educational AR. Our current application leverages the 2D content found in textbooks and overlays simple, interactive 3D content to provide students with additional pedagogical tools to support science learning. Using this application, students can develop a greater visual understanding of the structure of plant and animal cells. Overall, participant feedback is very positive and provides meaningful insights to inform the next stage of development and evaluation for this project. Our study results confirmed that integrating AR with textbook material supports individual student learning and can be leveraged to promote interest in STEM subjects. We believe that the use of AR technologies and others will continue to flourish in the educational field.

One limitation of this exploratory study is that we conducted usability testing with adult learners, which is a common approach to preliminary usability studies in HCI. We acknowledge that the results from this test may differ somewhat from usability studies conducted with the target population. In future work, we plan to conduct comparative usability studies with the target age group in order to identify any differences in usability (e.g., based on cognitive differences) prior to running longitudinal studies on learning effects in the classroom. After analyzing the results of the participant questionnaires, we were encouraged to continue working on educational AR applications to support STEM learning. In future work, we will apply this research in other areas of STEM education, mapping interactive AR content onto existing classroom learning materials. We intend to work closely with teachers and students in grade eight classrooms in order to better understand the benefits and limitations of such applications in real-world contexts. We hypothesize that a co-design approach to AR pedagogical tools will help researchers and educators overcome the design pitfalls and novelty effects currently impeding work in this area.

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