Science Spots AR: a Platform for Science Learning Games with Augmented Reality

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Abstract

Lack of motivation and of real-world relevance have been identified as reasons for low interest in science among children. Game-based learning and storytelling are prominent methods for generating intrinsic motivation in learning. Real-world relevance requires connecting abstract scientific concepts with the real world. This can be done by situating learning processes in real-world contexts, and by bridging the virtual content and the real world with augmented reality (AR). We combined these ideas into a Science Spots AR platform on which context-aware storytelling science learning games can be created. As proof-of-concept we developed and evaluated Leometry game, which contains geometry problems based on the Van Hiele model. This paper's contributions are as follows: 1) concept and architecture of Science Spots AR, 2) design and implementation of the Leometry game prototype, and 3) mixed-method formative evaluation of Leometry with 61 Korean 5th grade elementary school children. Data retrieved by questionnaires and interviews revealed that the students appreciated Leometry despite its minor shortcomings, that the platform's concept is feasible, and that there is potential for building science learning games. These results are useful to educators, computer scientists, and game designers who are interested in combining context-aware learning, AR, and games.

Keywords: context-aware, augmented reality, games, science learning, storytelling

Biographies:

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Compliance with Ethical Standards: Research involves children as participants. Before running the experiment with the children, we acquired data collection and media usage permissions from their guardians. Furthermore, children’s personal data such as names were not collected.

Conflict of Interest: The authors declare that they have no conflict of interest.

Introduction

A significant problem in science education lies in the students' attitudes towards science (Osborne, Simon, & Collins, 2003). Research suggests that for the past few decades, school children's interest in science education has been declining for many reasons with the recurring themes being lack of motivation (both extrinsic and intrinsic) and lack of relevance to the real world (Osborne et al., 2003; Porter & Parvin, 2008; Van Aalsvoort, 2004). The latter challenge stems from the deemed irrelevance of theoretical science education, particularly physical science, to everyday experiences (Osborne et al., 2003; Porter & Parvin, 2008). Classroom-centered instruction makes it difficult to organize contextually relevant learning activities on real-world objects and phenomena. Extracurricular science-related activities have been recognized to be particularly important for motivating students towards science (Fortus & Vedder-Weiss, 2014). Furthermore, UNESCO has recommended that the role of science and technology in the students' worlds outside of school should play a powerful motivating role, and that science education should move progressively towards a context-based approach in a real world (Fensham, 2008).

The term “science” can be understood in different ways depending on the viewpoint. We follow the definition of science as an umbrella term covering both formal and empirical sciences. Formal sciences study formal systems, and they include disciplines such as mathematics, computer science and statistics. Conversely, natural and social sciences belong to empirical sciences, and they apply empirical methods to study the world. The results presented here are applicable to formal and empirical science education.

To tackle the aforementioned challenges of motivation and real-world relevance in science education, we seek to merge digital technologies, storytelling and games, and deploy them outside classrooms with digital science learning content. We use augmented reality (AR) and context-awareness to bridge the digital game world and the real world. In AR, virtual content, such as three-dimensional (3D) models, is placed on top of a real-world view (e.g., using a camera). Through context-awareness we can provide contextually relevant learning content to the learner (Laine, 2012).

In this paper, we define the concept and architecture of the Android-based Science Spots AR (SSAR) platform that enables the construction of story-driven learning games for science education using AR and context-awareness. Game stories consist of Science Spots, which hold one or more educational challenges connected to a location. To test the conceptual feasibility of SSAR, we create a proof-of-concept storytelling game Leometry for learning geometry, and perform a formative evaluation on it with 61 Korean 5th grade elementary school students by using a mixed-method approach with questionnaires and interviews. Our findings are useful to educators, computer scientists, and game designers who are interested in context-aware learning, AR, and games.

Background

In following subsections, we analyze the existing literature on storytelling in education, learning with AR, and context-aware learning games.

Learning through Storytelling

Humans have been telling stories throughout history. “We are, as a species, addicted to story. Even when the body goes to sleep, the mind stays up all night, telling itself stories” (Gottschall, 2012, p. 14). Storytelling is a powerful learning tool that promotes motivation (Alterio, 2003). Storytelling as an instruction method has many other advantages, such as developing ways of knowing and dialoguing about issues, getting students involved, and making information memorable (Lordly, 2007; Rossiter, 2002), as well as helping to develop interaction among students (Alterio, 2003).

Digital storytelling, where digital media is used to express, store and share stories, introduces new learning possibilities. When used in education, digital stories allow interactivity and facilitate options for non-linear storytelling (Duveskog, 2015). Digital storytelling also promotes 21st century skills, engages teachers and students, and encompasses multiple literacy skills (Robin, 2008). Hung et al. (2012) suggest that combining project-based learning with digital storytelling enhances students' science learning motivation, problem-solving competence, and learning achievement.

Using narratives in games can support learning (Lester et al., 2014). Storytelling has been used in several science learning games (Klopfer & Squire, 2007; Laine, Islas Sedano, Sutinen, & Joy, 2010; Lester et al., 2014; Nygren, Sutinen, Blignaut, Laine, & Els, 2012), and it has been shown that the use of storytelling in game-based learning can provoke intrinsic motivators such as altruism and fantasy (Nygren et al., 2012).

Augmented Reality in Education

Augmented reality (AR) is a technology in which virtual content such as 3D models, animations, two-dimensional (2D) images, or annotations are placed on top of a real-world view. This is typically implemented by using a camera, visual markers, machine vision algorithms, and content rendering. By analyzing the camera feed, the AR software determines where the augmented scene is to be located in relation to the camera, and draws a virtual content layer on top of the camera image. The AR content is updated in real-time as the user changes the camera's position.

AR has been shown to boost motivation in educational applications (Balog & Pribeanu, 2010; Dunleavy & Dede, 2014). The following examples demonstrate other affordances and constraints in AR-based learning. Kaufmann and Schmalstieg (2003) proposed a collaborative AR application where students construct 3D mathematical and geometrical models in a shared AR workspace. Their evaluation results suggested that while an AR-based construction environment encourages experimental learning and improves spatial skills, hand-eye coordination is difficult due to lack of haptic feedback. Furthermore, the system required the users to wear uncomfortable head-mounted displays. Chen (2006), who explored the use of AR for learning chemical structures, also found that the lack of physical contact can be an issue for some students. They concluded that AR is particularly suitable for making abstract concepts more concrete and accessible. Finally, AGeRA is a geometry learning system that combines a book and an AR software on a mobile phone that is capable of placing virtual content on the pages of the book (Dionisio Correa et al., 2013). Through teacher and student evaluations, the authors found that the AGeRA system is suitable for learning geometry, and proposed several affordances such as intuitiveness, attractiveness, and increased motivation.

Perez-Sanaugustin et al. (Perez-Sanagustin, Hernandez-Leo, Santos, Delgado Kloos, & Blat, 2014) explored how AR and other technologies (e.g., LMS, NFC, and GPS) can bridge formal, non-formal, and informal settings to support blended learning in location-aware tours. Results suggest that AR and other mobile technology facilitate the data flow between pedagogical settings, thus strengthening connections among blended learning activities. A literature review by Dunleavy and Dede (2014) discovered 14 AR-based games and interactive applications for science education, suggesting that AR is best suited for exploratory, inquiry-based activities outside classrooms. With the help of smart devices and AR, difficult scientific concepts can be concretized and simulated by using a combination of real and virtual objects.

Many of the games surveyed by Dunleavy and Dede are location-aware simulations in which the player learns by scientific inquiry. These games have story-driven goals such as "investigate a disease outbreak and attempt to contain it" (Outbreak at MIT), "investigate the causes behind why a while has beached itself" (Gray Anatomy), or "explore the African savannah as a pride of lions to learn about the ecosystem and behavior of animals" (Savannah) (Dunleavy & Dede, 2014). AR in these games is more location-based than vision-based. To our understanding, there is a tight coupling between the games and their respective contexts, and there seems to be little support for reusability of the game stories, learning materials and other assets across contexts.

For the sake of reusability, researchers have built and used toolkits for creating location-aware AR applications with educational features (e.g., ARIS (Martin, Dikkers, Squire, & Gagnon, 2014), TaleBlazer (Lehmann, 2013), FreshAiR

(Kamarainen et al., 2013)). However, these toolkits do not allow direct interaction with AR content, and their context-awareness is limited to location-awareness.

Context-aware Games in Science Education

Smartphones with sensors have enabled context-aware learning experiences that complement classroom pedagogy by involving the context in the learning process. A context-aware learning space can detect and act upon changes in the learner's context (e.g., location, environment, state of body and mind, social group), and provide learning content relevant to the learner's situation (Laine, 2012). The extent to which a learning space is context-aware depends on its technical capabilities. Requirements for this stem from the desired learning experience – what does the learning space need to know about the context to provide a purposeful learning experience? Examples of context data sources include location (Facer et al., 2004; Perez-Sanagustin et al., 2014) and environment (Laine et al., 2010; Rogers et al., 2004).

A typical scenario of context-aware learning is a problem-based learning environment where the learner solves contextually relevant problems and the teacher assumes the facilitator's role in the learning process (Hmelo-silver & Barrows, 2006). A challenge with context-aware learning and mobile learning in general is that the learning applications must compete with other mobile applications (e.g., Youtube, instant messengers) for the learner's attention (Dirin & Nieminen, 2013). A good way to capture a young learner's attention is an intriguing game. Games have been shown to possess intrinsic motivators (Garris, Ahlers, & Driskell, 2002; Malone & Lepper, 1987; Nygren et al., 2012; Sweetser & Wyeth, 2005) that facilitate engagement and can help achieve the state of flow in the learner. Furthermore, learning through play has a long history (Reilly, 1974) and has been shown to be effective in the learning processes of children (Alessi & Trollip, 2001). Learning games have also been recognized to possess a great potential to help students to develop understanding of science concepts and processes (Lester et al., 2014). Combining games and authenticity in the real world enables learners to see and interact with natural phenomena, and it consequently enhances students' motivation (Honey & Hilton, 2011; Liu, Rosenblum, Horton, & Kang, 2014).

Context-awareness complements the motivational benefits of game-based learning by enabling situated, authentic and personalized learning experiences (Jeng, Wu, Huang, Tan, & Yang, 2010) with additional characteristics of permanency, accessibility, immediacy, interactivity, calmness, and seamlessness (Liu, Tan, & Chu, 2009). The following examples use context-awareness to deliver situated science learning experiences that leverage the motivational power of games.

UFractions (Nygren et al., 2012) is a storytelling fraction learning game that utilizes a mobile device and wooden fraction connected to the story. This connection between physical and virtual game content was found to elicit several motivators commonly present in game-based learning. However, the game does not utilize other aspects of the physical context than the fraction rods. Via Mineralia is a treasure hunt game that uses location awareness for learning about a mineral exhibition in a museum (Heumer, Gommlich, Jung, & Mueller, 2007). In evaluation, the game was found to motivate the participants to explore the museum and read information from placards. Competitiveness of the game was identified as a powerful motivator.

Biology and environment have been particularly common topics for context-aware science learning systems. Savannah is a location-aware game where the player learns about lions' behavior by exploring a virtual savannah acting as a lion (Facer et al., 2004). Assuming the role of a lion in a real world setting was found to be particularly engaging to the players, but the disjuncture between the game world and a real savannah disturbed the game experience. Bringing the player closer to the flow with an appealing story, for example, could prevent this clash of realities. EULER is an educational platform that combines RFID and mobile devices to provide situated learning experiences (Liu et al., 2009). The authors used the platform to develop a treasure hunt game for learning natural science in a park. Their evaluation results indicated that EULER improves learning, increases motivation, supports a variety of learning resources, and stimulates students' creativity through problem solving. No shortcomings were reported, but EULER's support for game-based learning is limited. Finally, Ambient Wood takes students to a field trip in a forest to learn about ecology through mobile devices and environmental sensors (Rogers et al., 2004). Although Ambient Wood is not a game, its evaluation revealed affordances that relate to many context-aware educational games, such as connecting virtual learning content to the physical world and engaging with the environment.

Based on these examples it is clear that the combination of game-based learning and context-awareness can not only increase motivation but also boost the learning experience by bridging the virtual game world and the physical world. This connection between the two worlds is likely to increase real-world relevance in learning abstract topics.

The Science Spots AR Concept

We combine the affordances of storytelling, gaming, context-awareness, and AR to propose a Science Spots AR (SSAR) learning platform that can assist learners in comprehending scientific topics such as geometry and kinetics in an enjoyable manner. The goal of the platform is to provide game-based learning environments to help students understand different scientific concepts through interaction and experimentation with real and virtual objects. The innovativeness of SSAR stems from the way in which the key components – storytelling, gaming, context-awareness, and AR – are combined and can be reused in different games created on the platform.

To increase student engagement, the learning content in SSAR is embedded in storytelling games. Each game has a specific science topic and virtual characters that interact with the learner. These characters guide the learner through a story that is divided into chapters. Chapters are composed of Science Spots, which hold one or more challenges interleaved by story snippets. Each Science Spot is connected to a location and is activated through interaction with an AR map at that location. AR can also be used in individual challenges. A story can have multiple paths and difficulty levels. Challenges, which should be grounded on pedagogical theories, may utilize context data (e.g., location, weather or the user's movement) as well as real and virtual objects. For example, a game on biology might have a challenge related to a virtual squirrel emitting sounds typical to squirrels and sitting on a real tree branch. This context-sensitive combination of the real world and the virtual game world can bring multi-sensory learning experiences to any physical context.

Game authorship is assigned to teachers and students via a Game Design Tool (GDT). Authored games are stored on the SSAR server from where they can be shared, searched and downloaded by the learners. The server also hosts a Learning Process Monitor (LPM) that allows an educator to analyze students' performance and detect when they are stuck in the learning process. LPM has two modes: 1) real-time mode for monitoring a game in progress, and 2) retrospective mode for visualizing and analyzing data collected over game sessions.

Smartphones, AR and context-awareness enable many challenge solving methods such as: 1) solving the challenge on the smartphone, 2) solving the challenge by interacting with the AR content, 3) observing, estimating, manipulating or measuring a physical object, and reporting the result via the smartphone, and 4) searching a physical object or a location, and reporting its discovery through an AR interaction or a smart tag (e.g., bar code or NFC). These methods can be used to connect the virtual and the real-world contents. Furthermore, Table 1 shows how context-awareness and AR can be utilized in game challenges.

Table 1. Context-aware challenge examples

Challenge example
Answer a quiz on the effects of current weather to a nearby tree.
Measure the amount of light/humidity/etc. at different locations to determine the optimal conditions for a given plant.
Interact with an AR model representing an ancient museum object with other nearby players.
Calculate how many footballs could fit on a schoolyard by using GPS measurements.
Estimate a distance or an area, and use GPS to confirm the result.
Arrange objects made of different materials (e.g., rock, tree, plastic, metal) by density.
Exceed given acceleration (e.g., 3*g) by swinging arm quickly.
After measuring your jump height with smartphone, calculate how high you would have jumped on the Moon.

Record running speed/acceleration onto a coordinate system using a model diagram.
Practice orientation with a digital compass.
Identify different 2D and 3D objects from the surroundings. Calculate their area and volume.
Calculate target heart rate for exercise and use a heart rate monitor to achieve it.
Use AR to visualize how a physical 3D object (e.g., a trash bin cylinder) is constructed out of 2D objects.

To illustrate the platform's operation, let us consider a fractions learning game. Before starting the game, the students (or teachers) create their own game environment by deploying the AR targets around their school surroundings according to the game's instructions. Thus, the students can decide which objects in their environment will be part of the game. For example, if the students are supposed to first solve a problem related to a tree, they could put target 1 on a nearby tree trunk, thus establishing the first Science Spot in the game. Further, if the second problem is related to a rectangle, they could find a rectangular object from their surroundings and put target 2 there to mark the second Science Spot. Targets are automatically geotagged to allow GPS navigation if the game is to be played outdoors. In the fractions game, the Science Spot 1 challenge by the tree could show a 3D picture of a leopard climbing a tree and include the following task related to the story:

Senatla starts to climb a 10 meters high tree. First he climbs up to the branch at the ¾ of the tree's height. Then he descends ½ of the tree's height. How high is Senatla now in the tree?

Science Spot 2 could include an AR view of a savannah with a territorial rectangle and the following challenge: "Mother leopard's territory is shaped like a rectangle of 10 km height and 15 km width. How large a territory the mother leopard has in km^2?”

When playing the game, the students move from one AR target (i.e. Science Spot) to another, according to the storyline. At each spot, there can be one or more challenges to solve. The player solves the challenges by interacting with virtual objects or by giving an answer on the smartphone, as discussed above.

The Science Spots AR Architecture

SSAR is based on a distributed architecture (Figure 1) that is both portable and extensible. Portability ensures that the platform can be used across contexts as long as the learning content is prepared appropriately for the target group of learners. Extensibility sets the foundations for future development and adaptation by facilitating the reuse of code and features. In the following sections, we describe the platform architecture in detail. The server module (dotted border) is currently under construction.

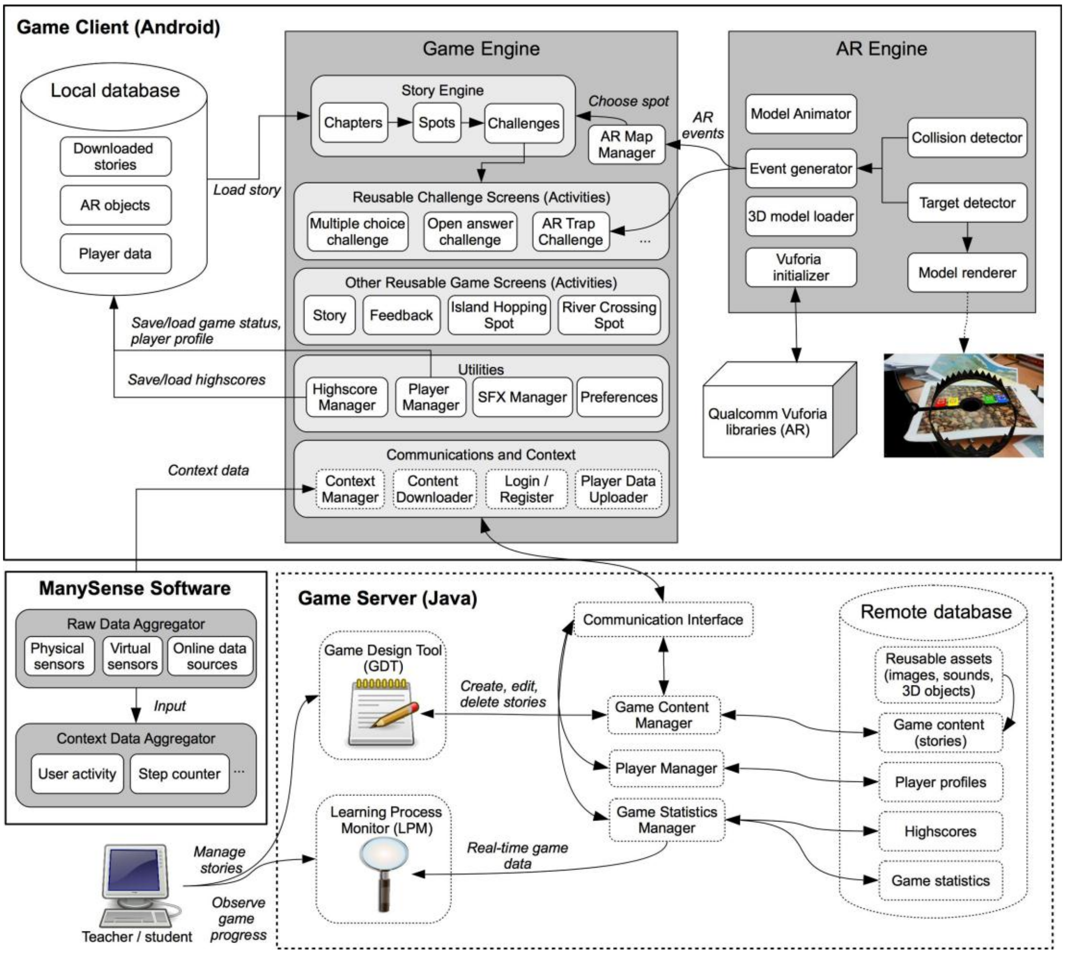

Figure 1. Distributed architecture of SSAR

The game client

The game client software, which is visible to the player, is divided into two parts: Game Engine and AR Engine. Game Engine contains game logic and features other than AR. Story Engine loads game data from a local database and manages the player's progress through the game by showing the appropriate screen at each stage. It contains chapters, spots, and challenges, following the story structure. AR

Map Manager is a special component that takes care of the transitions between spots. Story Engine triggers it at the end of each spot to show all the available spots on an AR map.

We designed Game Engine so that it contains reusable screen templates. For example, logic of the challenge screen templates can be reused by replacing their content. Similarly, templates for the story screen, feedback screen, and spot screens can be reused within a game or between games. New screen templates can be added in the future.

Game Engine has utilities and communication tools that are essential to the platform's operation. Player and Highscore Managers keep track of the player's progress real-time and historically, respectively. These statistical data are stored in a local database. If the game crashes or the player wishes to stop the game and continue later, Story Engine can request the latest game status from Player Manager and let the game continue from there. Sound Effects (SFX) Manager plays the sound effects embedded in a game. Preferences allow the user to change certain variables in the system, such as the player profile and server connection information. Content Downloader and Player Data Uploader manage the browsing and retrieving of stories from the server, and the transmission of updated player data to the server, respectively. Login and registration features enable online player profiles, which can later be used for multiplayer challenges, for example.

AR Engine handles all details related to AR, and it is based on the Vuforia[1] software. AR engine notifies Game Engine about events such as when AR objects appear or collide. Using these notifications, we can create custom AR challenges in Game Engine.

The AR content can be reused in a three-step process as shown in Figure 2. First, a 3D model is defined in the Wavefront OBJ format. Second, a texture image file is defined to be the model's "skin". Third, rendering parameters such as model location, rotation, and scale are defined. AR engine uses these parameters to draw the model on an AR target.

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[1] http://www.vuforia.com

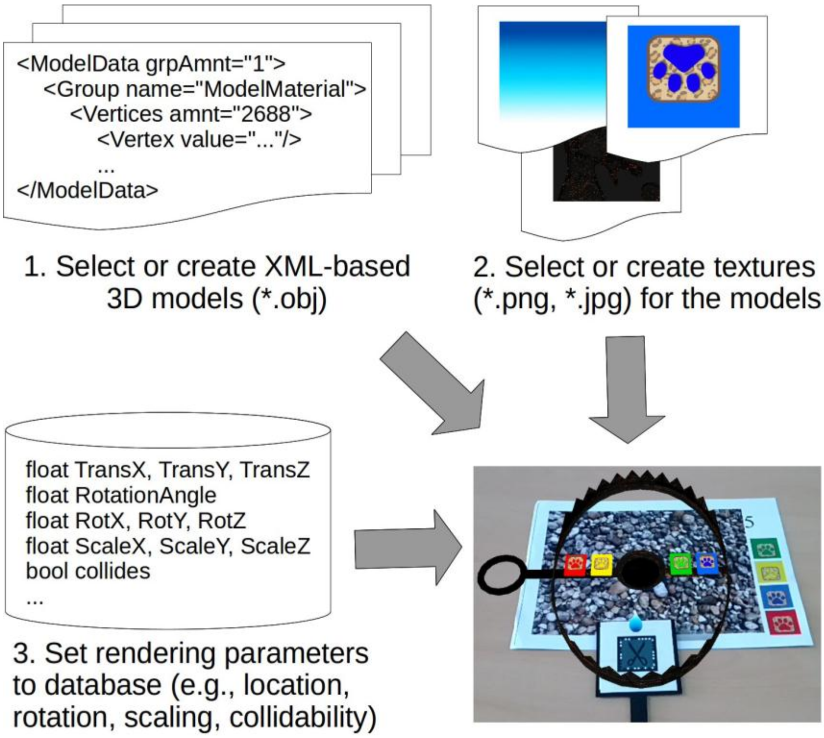

Figure 2. Reusing AR content

The game server

The game server, which is hidden from the players, accepts connections from game clients and redirects them to appropriate managers. A remote database holds the player data, media assets, and stories that can be downloaded by the game clients. Game Content Manager provides stories to the clients and to the Web-based Game Design Tool (GDT). With GDT, users can create their own stories by graphically arranging screen templates into a directed graph and connecting the screens to specific locations on a map. Users can also create or reuse media assets, such as graphics, sounds and 3D models. Table 2 exemplifies reusable assets that were created for Leometry; background sounds and images are customizable in all screens.

Table 2. Examples of reusable assets

Asset	Parameters
Story screen	Title, text, images
Multiple choice challenge	Introduction, question, choices, correct answer(s), hint, feedback, points
Open answer challenge	Introduction, question, answer(s), hint, feedback's, points
AR trap challenge	3D model, texture, pressure plate images, time limit, scaling, rotation,

	AR target, points
AR map	3D models, textures, scaling, rotation, AR target
River crossing spot	Clickable area links to challenges, the order of clicking
Island hopping spot	Clickable area links to challenges, the order of clicking
Game characters	Names, posture images
Main menu	Background, button images

Game Statistics Manager mediates game session data to Learning Process Monitor (LPM). LPM records time-stamped data whenever the player interacts with the game. This data can reveal information such as points of a player, current challenge, time spent on each screen, the numbers of solving attempts and hint requests.

ManySense software

The games based on SSAR can use the ManySense software (Westlin & Laine, 2014b) to detect the user's context. For example, ManySense can tell the exact location of the user, the current weather condition, or whether the user is walking, running or standing still.

Raw Data Aggregator provides unified access to heterogeneous raw context data sources such as sensors and Internet services. Currently supported data sources include Android smartphone sensors, Sony SmartWatch SW2, Zephyr heart-rate monitor, OpenWeatherMap weather service, and Myo gesture armband. New data sources can be added fairly easily.

Context Data Aggregator simplifies the access to algorithms that produce higher-level context data. These algorithms receive raw context data from Raw Data Aggregator, and then process it. For example, a step counting algorithm converts raw accelerometer data into steps. Currently implemented algorithms can perform step counting, activity detection (standing, walking, running), and indoor positioning.

Game Engine's Context Manager mediates communications between game screens and ManySense. When a game screen wishes to get context data, it makes a request to Context Manager, which directs it to ManySense and passes the returned data back to the screen. Involving Context Manager as a mediator allows us to further process the context data, for example to convert location coordinates to Science Spot IDs.

Leometry

Leometry is a proof-of-concept game for demonstrating some of the features of SSAR. It aims to teach basic geometric shapes such as triangles, circles, and rectangles to 5^{th} and 6^{th} grade elementary school students in South Korea (11-12 years old in western age reckoning). There is one chapter with three Science Spots, which originally corresponded to the exhibition locations at the SciFest 2014 science festival held in Joensuu, Finland. After the festival ended, we transformed the game into a location-independent showcase of SSAR, and evaluated it in a Korean school environment.

Game features

Leometry uses storytelling to immerse players in an adventure on the African savannah. The story, written in English, Korean and Finnish, begins when two leopards, mother leopard and her cub Senatla, escape from poachers who have illegally captured them. The player's task is to help the leopards find their way back home. The road is filled with obstacles such as crocodile-infested waters and poachers' traps. The player is assisted by a dung beetle Pex who presents various geometry challenges and gives on-demand scaffolding hints. The Leometry story structure is depicted in Figure 3; here, interleaving story snippets have been omitted for the sake of clarity.

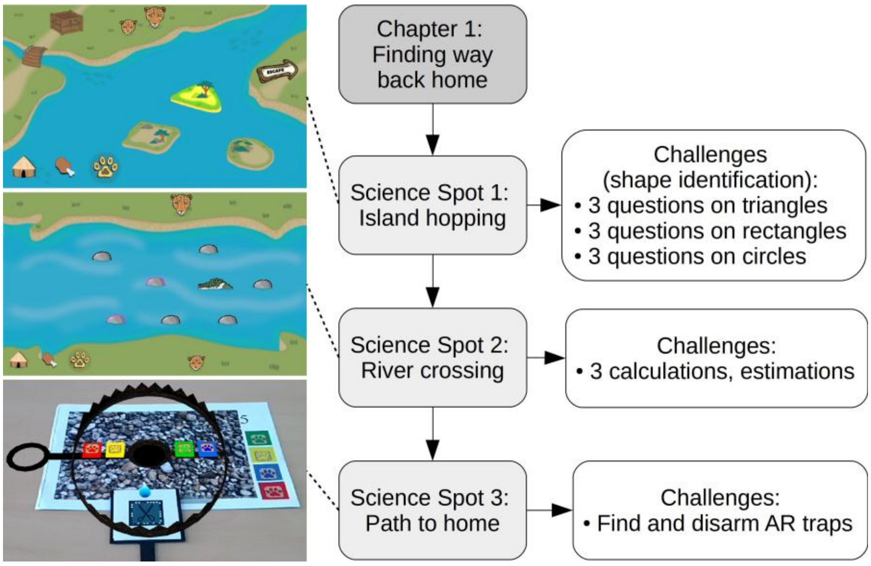

Figure 3. Leometry story structure

Figure 4 illustrates selected game screens. Screen A shows a scrollable story with text, images, and background sound. Screens B-D exemplify pedagogical challenges where the player must identify a valid shape (B, D) or count the number of valid shapes in a diagram (C). All these screens, as well as the spot screens illustrated in Figure 3, can be customized as explained above.

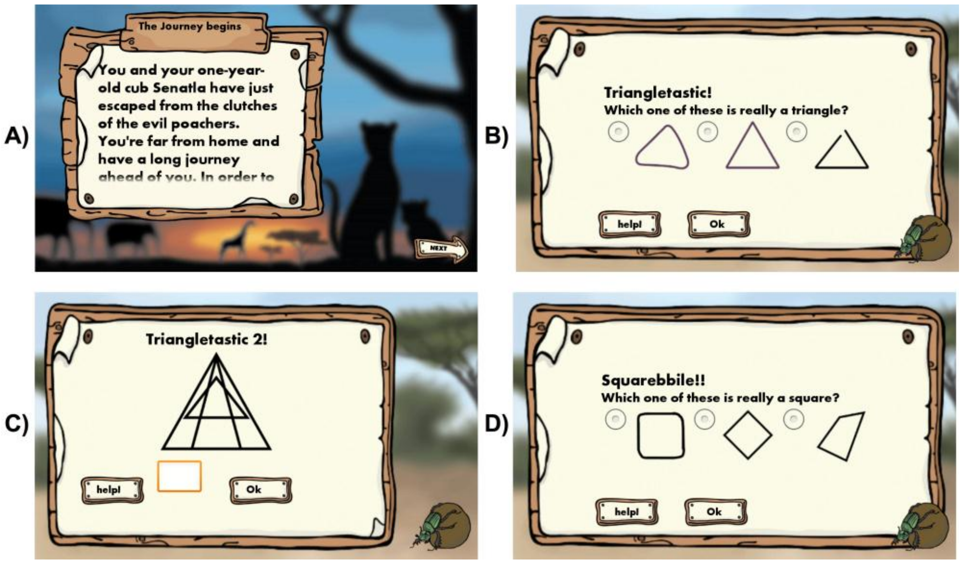

Figure 4. Leometry screen samples

Leometry's pedagogical challenges were prepared with Korean and Finnish mathematics education experts. These challenges are based on the Van Hiele model, which describes the process of geometry learning (Van Hiele, 1984). Figure 5 illustrates four levels of the model where the transition from one level to another is possible only if the earlier levels are accomplished. Because Leometry was created for elementary school students, we based its pedagogical challenges on the first two levels. Level 0 is the level of visualization where the learner can identify basic shapes by their appearance. At level 1, the learner can analyze a shape based on its properties, such as the number of sides or angles. Although we did not include level 2 in Leometry, it could be suitable for talented students at 5th or 6th grades (Wu & Ma, 2006).

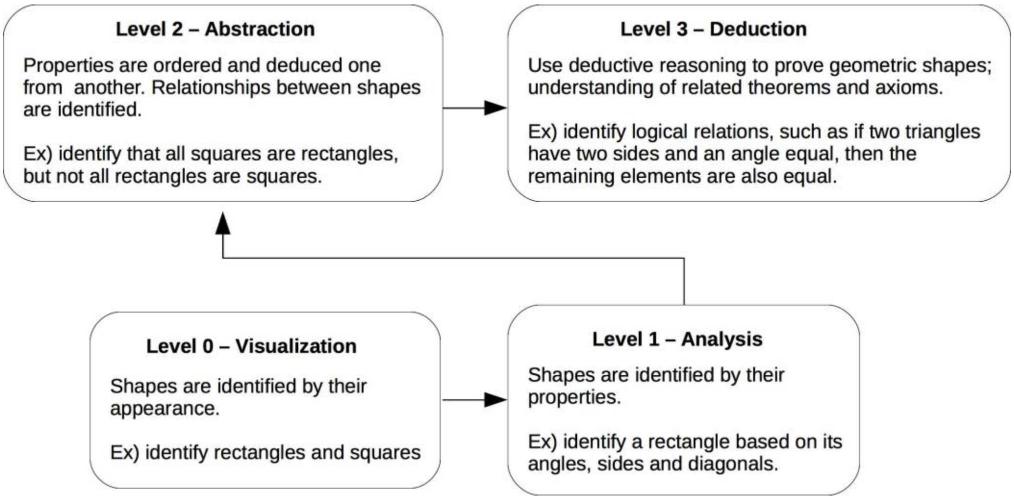

Figure 5. Levels of the van Hiele model (Van Hiele, 1984)

The AR features in Leometry do not contain any pedagogical objectives as they aim to demonstrate the platform's AR capabilities. These features are the AR map and the boss challenge (Figure 6). The AR map shows available Science Spots using AR. A real world map can be overlaid on top of the AR map, thus connecting the virtual map locations to physical Science Spots. To activate a Science Spot, the player must touch it with the dewdrop object drawn on the wand (top of Figure 6). The boss challenge involves finding and disarming traps deployed by poachers. After finding a trap target using the AR map, the player must carefully touch the pressure plates of the trap with the dewdrop in the correct order. A similar approach was used in our Calory Battle AR exergame (Westlin & Laine, 2014a), thus demonstrating AR Engine's reusability.

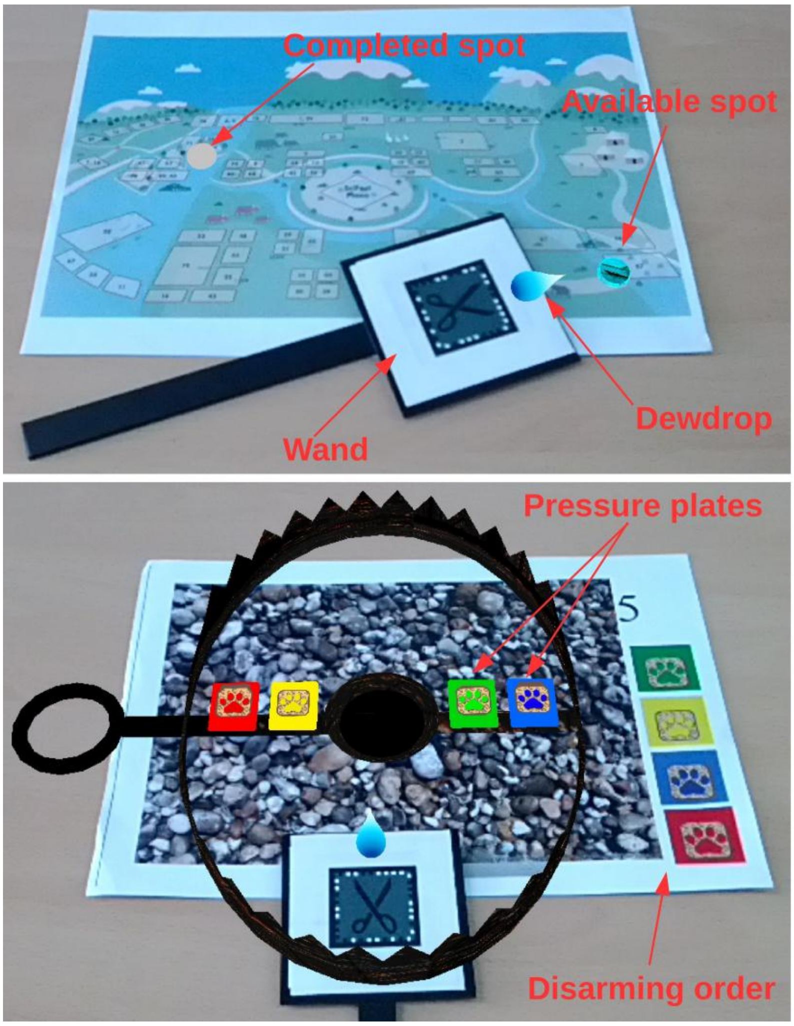

Figure 6. The AR features of Leometry: AR map with Science Spots (top) and boss challenge (bottom)

Design principles

We started developing Leometry by analyzing UFractions, an educational game that combines a mobile-based story with problem solving using physical fraction rods. UFractions has been found provoke intrinsic motivators that are not typical in mathematics classes (Nygren et al., 2012). Based on our analysis of UFractions and related literature, we established seven design principles for Leometry (Table 3).

Table 3. Leometry design principles

Storytelling	
Humor	Humor enhances the playful nature of interactive media. In Leometry, the dung beetle's discourse style is humorous, and the game challenges are presented in a humorous tone. Zillmann et al. (1980) discovered that the addition of humorous content produces superior educational results to non-humorous content in

	television programs for children. In another study, Dormann and Biddle (2006) discussed the role and the benefits of humor in educational games. They found that humor can sustain emotional and cognitive engagement, stimulate social presence, and increase enjoyability of the game experience.
Continuity	The continuity of storytelling in Leometry connects spot to spot, challenge to challenge, and chapter to chapter. This continuity strengthens the expandability of the game and supports long-term engagement of the players. Murray et al. (2012) used a recurring character for continuity as one of the elements of a companion IPad app for a TV series. In Leometry, the dung beetle Pex is a recurring *helper* who guides the player to reach a goal (e.g., find a way back home). His role is quite important because not only he provides pedagogical scaffolding, but he is also a character who realizes the two design principles of storytelling – humor and continuity – in the game.
User Interface	
Real-world references	The game characters and background art were modeled based on real-world reference images. We applied a cartoonish and lighthearted drawing style that we thought to be suitable for young players.
Legibility	Children's attention span can be estimated to last for 1-3 minutes for every year of their age; however, appealing media such as videogames and cartoons may capture attention for a longer time (Abadzi, 2006). To cater for children's short concentration ability, we emphasized legibility in the user interface design by following some of the widely used human-computer interaction design principles such as simplicity and consistency (Molich & Nielsen, 1990). For example, we used bold outlines on graphic elements and vivid colors inspired by African art to catch the players' attention. To simplify the design, we sought to eliminate unnecessary graphic elements such as tree leaves.
Pedagogical support	
Pedagogical grounding	Leometry's pedagogical challenges are grounded on the first two levels of the Van Hiele model, which describes the process of geometry learning (Van Hiele, 1984).
Scaffolding hints	The dung beetle provides on-demand scaffolding hints for each pedagogical challenge. These hints intend to direct the player towards the correct solution without revealing the solution.
Immediate feedback	Immediate feedback has been shown to increase learning and retention in quiz-like learning activities (Epstein et al., 2002), and it can also be beneficial for children's attention span (Abadzi, 2006). In Leometry, the dung beetle provides immediate feedback when the player gives an answer to a challenge.

While end-users did not participate in the game design, more than 50 of them provided valuable feedback when an alpha version was tested at the SciFest 2014.

Through this test, we identified several problems in the game (e.g., crashing, memory consumption, usability), which were addressed by the developers before evaluating the game in Korea.

Formative evaluation

Formative evaluation can be applied to educational technology development process in four phases: planning, design, production, and implementation (Flagg, 1990). In order to measure the conceptual feasibility of SSAR, we performed a formative evaluation in the production phase of Leometry. That is, a non-final version of the game was tested with a target group comprising 61 (52% male, 48% female) 5th grade students at an elementary school in Korea. The students were 12 years old according to the Korean age classification (11 years in western age reckoning). Almost all (93%) students owned a mobile phone and used it daily for texting (48%), talking (77%), photographing (38%), playing games (67%), and accessing social media (31%), thus indicating high mobile phone penetration at an early age. In the following paragraphs, we describe our data collection procedure and the obtained results in detail.

Data collection

Primary evaluation data were collected using a mixed-method questionnaire comprising Likert scale statements and open questions. The first part of the questionnaire collected data on the students' demographics, mobile phone usage, mobile gaming experience, and general attitude towards mathematics. In the second part, we surveyed the players' opinions on Leometry's motivational aspects, gameplay experience (e.g., likes, dislikes, and improvement suggestions), features, suitability, storytelling approach, impact, and user experience (e.g., graphics, sounds, and AR). Secondary qualitative data were collected by interviewing eight players to support the quantitative findings. In particular, we sought to uncover reasons for liking or disliking certain features of the game, problems faced by the players, insights on the user experience, and the game's deemed value as an educational tool. All data were collected in Korean and translated into English for analysis by an international research team. Research ethic requirements were met by acquiring data collection and media usage permissions. Furthermore, players' personal data such as names were not collected.

Before evaluation, the questionnaire was translated into Korean and the game client using Korean language was installed on a variety of Android smartphones and tablets. The data were collected in two separate classes in May 2014. Both 40-minute sessions were organized as follows: First, the teacher introduced the researchers to the children, after which the researchers took 5 min to explain the purpose of the research and the game concept, and how to interact with the AR content by using the wand. Then, the players were divided into teams of two to three students, and each team was given a smart device, printed AR targets, and a wand to play for 15 minutes. The researchers and the teacher made observations and assisted the players if they had problems during gameplay. Figure 7 shows the players solving geometry challenges. During the remaining 20 minutes, the players filled in the questionnaire and were allowed to ask clarifying questions about the statements. The teacher selected four players from each group, in total 4 males and 4 females, for interviews on the basis of their outspokenness. These one-by-one interviews were conducted about one week later due to lack of time on the gameplay day. During the interviews, the interviewees were allowed to review the game to refresh their memory.

Figure 7. Players solving Leometry challenges

It is worth noting that the game was played during ordinary class schedule and all pupils in the two participating classes were asked to play the game. Although none of the students expressed their wish to skip the game session, we acknowledge that this arrangement entails an ethical problem regarding voluntary participation.

Results

We analyzed three aspects of SSAR through Leometry: 1) features, 2) storytelling approach, and 3) impact. The results were derived from the quantitative questionnaire data and supported by qualitative excerpts from open questions and interviews. We analyzed the distribution of the quantitative data along the Likert scale and included the mean and standard deviation values for testing validity. Each figure shows the percentages of responses so that the distribution among the Likert options, ranged from 1 for "Strongly disagree" to 4 for "Strongly agree", can be seen. The original data had also "No opinion" answers, but these, together with omitted answers, were removed to emphasize the polarity of the results. A result is considered significant if the number of positive or negative answers exceeds 70% of the sum of positive and negative answers. The mean (μ), the standard deviation (σ), and the number of responses (N) are also given. The student quotes are suffixed with meta-data as follows: ([gender]-[id]). Age is omitted because all students were 12 years old.

Features

We measured the reception of Leometry's features by asking, "which features did you like?" Figure 8 presents the answers to this question. Solving problems (2) and playing with friends (7) received particularly positive ratings (98% and 90%, respectively). This is not unusual because challenge and social gameplay are well-known game motivators (Malone & Lepper, 1987; Nygren et al., 2012; Sweetser & Wyeth, 2005). These were also reported by the teacher who observed that the players were eager to solve the problems in order to move to the next level, and often, they were discussing and comparing the solution proposals among themselves. Furthermore, the qualitative expressions of the players show that a suitable level of challenge, perceived feeling of achievement (or failure), feedback, and competing with friends are among the possible reasons for why the aforementioned two statements were highly rated:

This game needs concentration because the questions were hard. (Male-46)

I felt some satisfaction when I cleared the stage. [...] I felt angry if I didn't clear the stage. (Female-40)

It was interesting when the character came out and I could feel some achievement if I solved the question. (Female-54)

Making a team and competing with each other to get the first place was interesting. (Male-03)

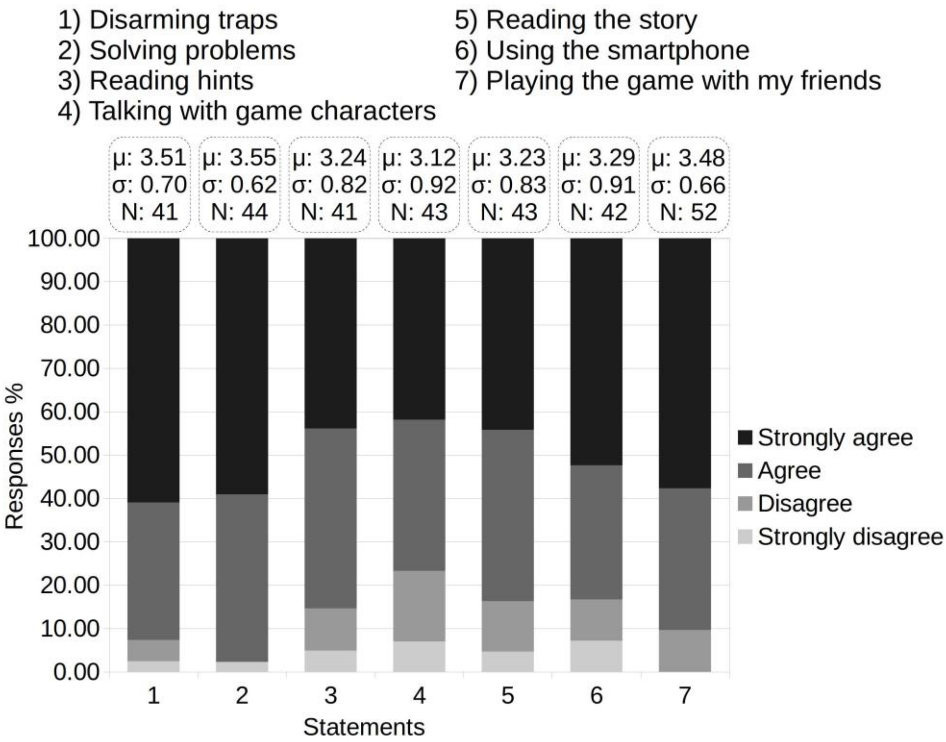

Figure 8. Results: Features

Although challenges were designed for 5th and 6th graders at Korean elementary schools, they were both easy and difficult at the same time, depending on the player. This shows that even in a fairly homogeneous group of students, different skills can exist. Therefore, it is important to support multiple difficulty levels in the game as these players suggest:

The questions were too easy. Maybe it could be better if difficulty of the questions was harder than current ones. It makes some kind of passion to solve a hard *question. Like, ``I REALLY want solve this question''. [...] When player clears a stage, the level of difficulty must go high. (Male-03)*

This game was hard to play for kids because it keeps turning off repeatedly and questions were too hard. [...] It could be better if levels were separated by difficulty. (Female-49)

The last comment above indicates a technical issue that two of the teams experienced, thus preventing them from finishing the game within allocated 15 minutes. The technology worked well for other teams.

The AR feature of disarming traps (1) was highly rated (93%). This result was confirmed by the interviewees of whom 7/8 reported disarming the traps to be the most amazing feature of the game. While AR's novelty can function as a powerful motivator, many students reported having problems with AR interactions that should be addressed in future research:

It was interesting but the AR system was hard to control. The waterdrop did not appear in proper position. (Male-47)

It was interesting that something came out from the paper, but it's inconvenient for player. (Female-41)

Using the smartphone to play (6) was considered likeable, thus confirming its suitability as a gaming tool. Statements related to story and content (3-5) were mostly answered positively (85%, 77% and 84%, respectively), but talking with game characters (4), in particular, received several negative responses. The results related to story are analyzed further below.

Storytelling approach

The reception of storytelling approach was measured by statements related to the Leometry story (Figure 9). The statements 3-5 in Figure 8 complement these findings. The story of the leopards (1) was considered interesting by a majority of the players (90%) and they strongly agreed about the importance of self-pacing (3). Most players (83%) reported that they would like to see other animals in the game (5), suggesting species like cat, dog, monkey, parrot, and tiger. The media used for the game characters and the background were designed on the basis of real-world references, and they were found to support the story well (6), as this comment confirms:

It looks like a real leopard and the background that describes the environment looks real. (Female-54)

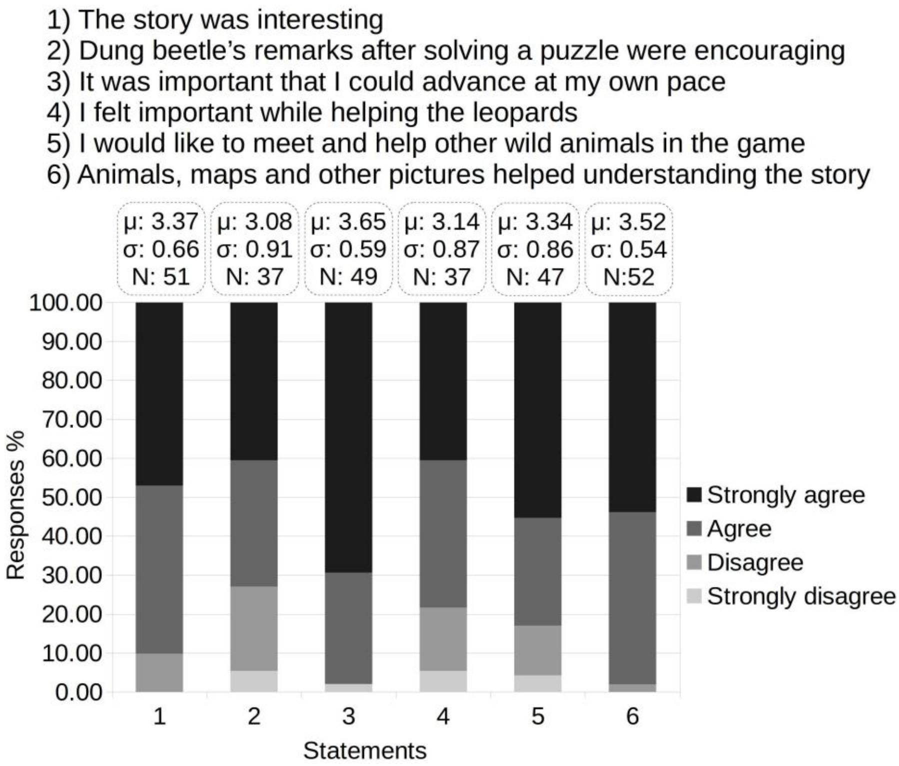

Figure 9. Results: Storytelling approach

Statements 2 and 4 measured the effect of the story-driven feedback mechanism in the challenges and altruistic immersion in the story, respectively. Both statements received a relatively high number of negative answers compared to other statements, thus calling for a future investigation on the underlying reasons. The result of statement 4 suggests that immersion in the story could be increased, even though these comments indicate immersion and altruistic experiences:

The contents were interesting. It made me to play this game more and more. (Female-6)

It was good that game is related to math and helping animals. (Female-29)

Impact

The aforementioned results indicate the positive reception of Leometry, but this does not tell about the game's impact beyond the gameplay experience. Figure 10 presents statements on the players' perceptions of Leometry as an alternative and interesting game-based learning tool, and the attitudinal influence that it may have. Statement 3 confirms previous results that gameplay was deemed interesting. Interestingly, although children generally enjoy playing games and many players agreed with statement 1 (79%), there were some who disagreed about playing as a good learning method. This could be due to insufficient exposure to Leometry and other educational games, too easy challenges, or personal preference. Irrespective of this, nobody rejected the idea that playing Leometry was more exciting than a normal class (2). The educational potential and the fun factor were expressed in many comments such as these:

People can learn math while they play this game. And it is more fun than what people have when they learn in class. (Female-54)

I can solve mathematical questions while playing this game. [...] It's really helpful for our education. (Male-39)

It's funny. Normally, we study by reading book. But with this game we can study by playing. (Female-08)

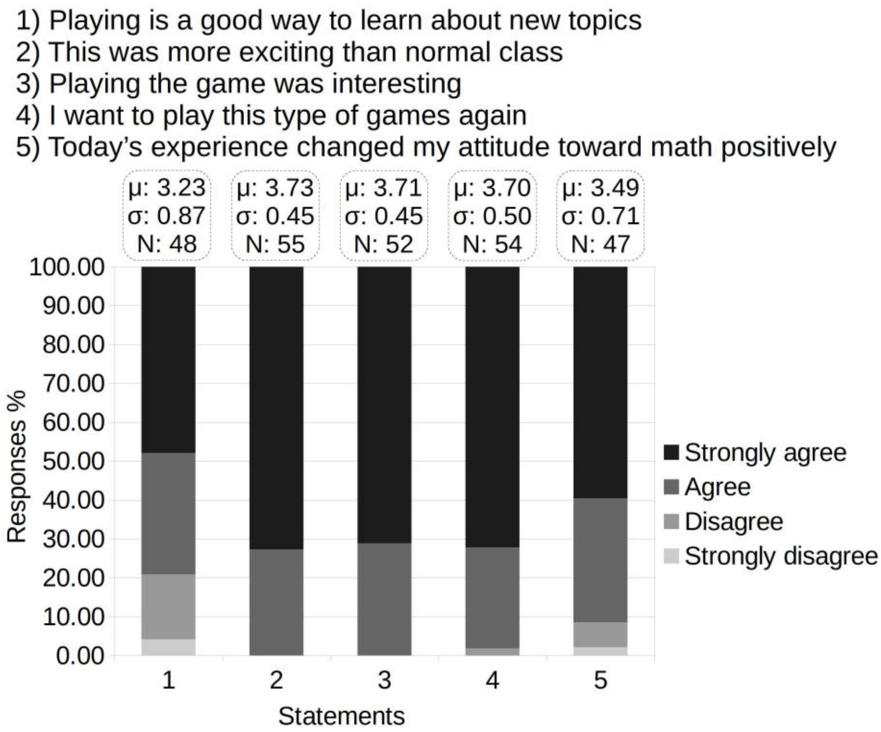

Figure 10. Results: Impact

By asking if the players would like to play other Leometry-like games (4), we intended to find out about SSAR's potential as an educational gaming platform. Positive responses (98%) encouragingly suggest that a combination of story, challenges, and AR could be feasible for science learning games. The results on the players' opinion about attitudinal change after playing the game are positive (91%), but it is important to note that this question was asked right after gameplay. Should the same question be asked after some months, the result may be different. Nevertheless, it shows that the game has potential for affecting the players' attitudes towards mathematics.

Discussion

The formative evaluation results suggest that the Korean children appreciated the game's features and its storytelling approach, and their answers regarding the overall impact were encouraging. Accordingly, there is a benefit to embedding pedagogical problems in a digital narrative that supports social collaboration and immediate feedback. The results also indicated that AR can be a powerful motivator, and other research has shown its potential in education (see Background).

We have only studied the conceptual feasibility of SSAR. Table 4 lists all feasibility dimensions that should be addressed in future research in order to claim full feasibility. For example, with respect to the contextual feasibility, it is unclear how well ManySense can support context-sensitive learning experiences. Similarly, reuse feasibility cannot be evaluated until we implement GDT. The conceptual design of SSAR can be useful to educators, computer scientists, and game designers who wish to combine context-aware learning, AR, and games, but its practical utility in some parts remains to be verified.

Table 4. Dimensions of feasibility

Feasibility	Description
Conceptual	The concept must meet the needs and the requirements of the target scenario and its users.
Motivational	The system should be motivating to encourage long-term use.
Pedagogical	The learning content and methods must be pedagogically grounded, and games must yield positive learning outcomes.
Contextual	The system must be able to adapt its behavior to the learner's context.
UX	User experience (UX), including the user interface, interaction, and instructions, must facilitate an easy and efficient use of the system.
Technical	The system must exhibit high performance, scalability, extensibility, and robustness with appropriate security features.
Reuse	The system must enable sustainable use of resources across contexts.

Although the quantitative results were mostly positive, qualitative data revealed several points for improvement. Firstly, the AR interaction was considered challenging by several players. Some of them blamed the technology by objecting that 3D objects were drawn in the wrong place. However, according to our observations, the AR interaction in Leometry requires high precision and patience, which some players lacked. Training with a video tutorial could be helpful to achieve these qualities. We will also review the existing AR interaction techniques and develop new ones in order to choose the best one for each scenario. Secondly, in rare cases, the game suffered from a fatal bug, which resulted in the crashing and restarting of the game. To alleviate this, we will thoroughly test the game before releasing it and introduce an automatic state saving feature, which allows the gameplay to continue from the last accessed challenge. Thirdly, some players criticized that same challenges were presented to all players irrespective of their geometry skill level. Following the concept of SSAR, Leometry should contain multiple levels of varying difficulty to accommodate a range of skills. Fourthly, although the game's user interface succeeded in creating a feeling of the African savannah, some players suggested improvements such as leopards could have bodies (now only heads), font size could be enlarged, and game characters could appear in 3D. We will conduct a user experience study in the future to investigate these matters in detail.

Successful games have high-quality content, which requires creative work on the story, graphics (2D/3D), interaction, and sounds. We have identified three problems in the content development for SSAR games. First, content development is at least as laborious as technical development, if not more so. In particular, the creation of realistic graphics and 3D models is time-consuming. In order to ease the process for SSAR game developers, we will create a library of reusable media assets, screen templates and 3D models that can be customized for each game, thus speeding up the game development. Second, screen size, resolution, memory, and processing power of end-users' mobile devices can vary greatly. Android ecosystem's fragmentation is a significant challenge for content developers to consider. While the Android design guidelines can be used for supporting heterogeneous hardware, creating screen layouts and graphics for all device profiles takes time. A system that automatically customizes content from one master copy would be very useful. Thirdly, creating pedagogically meaningful and versatile challenges is a key factor for successful learning games. Currently, Leometry contains only a few challenge types, which do not show the full potential of the platform. We aim to improve this aspect by creating constructive and context-aware learning challenges that provide alternative approaches to learning science (see Table 1).

The platform's AR Engine has some weaknesses to be improved in future development. It currently requires printed image targets to be deployed in the target context. This can be inconvenient in some scenarios because the printed targets, if forgotten, may turn into litter or be destroyed due to environmental conditions. An interesting future investigation is markerless tracking and real-world object recognition to remove the dependency on markers and image targets. Markerless tracking often depends on a dedicated database of images or the detection of the physical context around the user. To alleviate this, we aim to investigate a possibility to implement object recognition dynamically without a reference database. The second weakness of AR Engine is the lack of a 3D game engine that would facilitate the production of animations and other 3D game elements. In our AR Engine, animations and other model manipulations must be implemented manually. In the future, we will explore the possibility of utilizing Unity 3D or a similar game engine to remove this weakness.

This study has several limitations as follows. First, the implementation of the SSAR server is not yet finished. Second, Leometry does not take the advantage of context-awareness apart from location-awareness in trap searching. To fully utilize the affordances of context-awareness, and to be able to evaluate the platform's ability to increase real-world relevance, we will develop context-aware challenge templates with ManySense in the future. Third, the AR features of Leometry do not include any pedagogical objectives. We plan to improve this by, for example, adding geometric shapes on the pressure plates of the AR trap challenge and asking the player to select them in the correct order according to a property such as the number of angles or size of the area. Fourth, the platform was evaluated only from the conceptual perspective in a single experiment, thus disregarding the other dimensions of feasibility. We are particularly keen to study the platform's motivational, pedagogical, and technical feasibilities in longitudinal experiments. Finally, the formative evaluation was not based on any technology acceptance model. To alleviate this, we propose to establish a technology acceptance model for the purpose of evaluating SSAR using existing models for mobile learning (Liu, Li, & Carlsson, 2010) and augmented reality (Yusoff, Zaman, & Ahmad, 2011).

Conclusion

The SSAR platform has conceptual similarity with physical playgrounds where children use multiple senses to learn about the world through play at various activity spots. It aims to stimulate and engage children, allowing new dynamic opportunities for playful interaction and learning to emerge. Games developed on SSAR can concretize and simulate abstract scientific concepts using a combination of real and virtual objects in a fun way. The platform enables science learning anywhere and at any time through contextualized learning experiences, and the creation of learning materials is distributed among users via GDT. In our vision, SSAR could introduce science learning games to schools, parks, backyards, streets and forests where players of different backgrounds and skills assemble to learn science in an engaging way.

SSAR could be used in other educational subjects as well through parameterized screen templates (e.g., story, challenges). Pedagogical efficiency of the platform stems from the learning content placed inside these templates. In the future we can expect to see templates specifically designed for pedagogical use, such as a learning log or an experiment recorder.

The next research steps include finishing the SSAR platform implementation, evaluating it by other feasibility dimensions (e.g., pedagogical, contextual, and motivational, reuse), developing and evaluating more science learning games, and investigating the possibilities of utilizing the platform outside science learning.

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