ScienceSpots 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. Gamification 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 ScienceSpots 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 ScienceSpots AR, 2) design and implementation of the Leometry game prototype, and 3) mixed-method 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.

Index Terms—context-aware, augmented reality, games, science learning, storytelling

1 Introduction

SCIENTIFIC achievements are at the heart of our society as they deeply affect how we perform our everyday activities. Science has enabled motorized vehicles, home appliances, and portable gadgets that make our lives more convenient, while the knowledge of medicine grants us a high life expectancy. As scientific advancements spread to new areas, it is clear that we need to train a new generation of scientists who will continue our legacy of scientific journey for the human race. Science training is currently conducted by schools with versatile curricula around the world. The quality of such science education is mostly adequate, but a significant problem lies in the students' attitudes towards science [1], which negatively affect the number of trained scientists. 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 [1], [2], [3]. The latter challenge can be partly attributed to classroom-centered instruction, which 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 [4]. 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 [5].

To tackle the motivation challenge, we merge three things that children are comfortable with–digital technologies [6], storytelling and games–and deploy them outside classrooms with science learning content. Gamification has been defined as "the use of game design elements in non-game contexts" [7] and can increase intrinsic motivation in learners [8], [9], [10]. Storytelling has also been shown to motivate and benefit learning [11], [12], [10]. Intrinsic motivation facilitates immersion in the flow [13] where the learner becomes highly motivated to perform an activity. This should be the goal of any learning activity, and we can use gamification and storytelling to achieve this goal.

The lack of real-world relevance can be mitigated by involving the real world in the learning process. Embedding of digital learning content in a real-world environment can be achieved with augmented reality (AR) in which virtual content, such as three-dimensional (3D) models, is placed on top of a real-world view (e.g., using a camera). We can further increase real-world relevance by context-awareness to deliver context-sensitive content to the learner [14]. Thus, learning experiences become relevant to real-world contexts outside the classroom. Several context-aware learning spaces have been proposed (e.g., [15], [16], [17], [18], [19], [14]), but most of them are technically outdated, do not support AR, or lack reusability.

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.

In this paper, we define the concept and architecture of an Android-based ScienceSpots AR platform that enables the construction of learning games for science education using AR and context-awareness. The platform allows children to learn science through story-driven gameplay. AR is used for bridging the gap with the real world with virtual learning content. The platform has conceptual similarity with physical playgrounds where children use multiple senses to learn about the world through play. It aims to stimulate and engage children, allowing new dynamic opportunities for playful interaction and learning to emerge. To test the conceptual feasibility of ScienceSpots AR, we create a proof-of-concept storytelling game Leometry for learning geometry, and evaluate 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. For example, an educator could use the platform to create games and follow the players' learning processes in real time.

2 Background

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

2.1 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 uses this information to draw 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. To determine the scene's location, the AR software uses computer vision algorithms to track real objects or fiducial markers. Tracking fiducial markers is easier as the algorithm knows exactly what it is looking for, but the markers must be deployed before the application can be used. Markerless tracking techniques are more complex and are typically based on image recognition or detection of the user's surroundings with GPS, sensors, and other devices.

Kishino and Milgram [20] defined AR as a subset of mixed reality (MR) where a real environment is augmented with virtual elements. Azuma [21] defined AR as a variation of virtual reality that helps users to see the real world through virtual objects. As FitzGerald [22] has stated, "one of the most compelling affordances of AR is its resonance with the immediate surroundings and the ways in which information can be overlaid on these surroundings, enabling us to learn about and annotate our environment." Application developers have started to understand this affordance, and the number of AR applications on smart devices is growing rapidly [23]. For the educational potential of AR this is significant because smartphones are popular among students. For example, 69% of South Korean elementary, middle, and high school students owned a smartphone in 2013 [24].

AR has been shown to boost motivation in educational applications [25], [26]; some examples of this are as follows: Kaufmann [27] proposed a collaborative AR application where students construct 3D mathematical and geometrical models in a shared AR workspace. Chien et al. [28] utilized AR to create an interactive learning system helping medical students to understand and memorize a 3D anatomical structure. AGeRA is a geometry learning system that combines a book and an AR software capable of placing virtual content on the pages of the book [29].

A recent article in IEEE Transactions on Learning Technologies explores 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 [30]. 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 discovered 14 AR science simulation games [26], 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.

Researchers have built and used toolkits for creating location-aware AR applications with educational features (e.g., ARIS [31], TaleBlazer [32], FreshAiR [33]). To our knowledge, these toolkits do not allow direct interaction with AR content, and their context-awareness is limited to location-awareness.

2.2 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, and provide learning content relevant to the learner's situation [14]. Context includes not only physical location but also environmental parameters, states of the learner's body and mind, social groups, and any other information that constitutes the learner's situation. Thus, context-awareness can facilitate learning by the provision of the right resources at the right situation. 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 [17], [30] and environment [15]

Learning applications smartphones can enable timely access to context-sensitive learning resources. A combination of these technologies can be used for establishing a problem-based learning environment where the learner solves contextually relevant problems and the teacher assumes the facilitator's role in the learning process [34]. However, 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 [35]. A good way to capture a young learner's attention is an intriguing game. Games have been shown to possess intrinsic motivators [8], [9], [36], [10] that facilitate engagement and can help achieve the state of flow in the learner. Furthermore, learning through play has a long history [37] and has been shown to be effective in the learning processes of children [38]. Learning games have also been recognized to possess a great potential to help students to develop understanding of science concepts and processes [39]. Combining games and authenticity in the real world enables learners to see and interact with natural phenomena, and it consequently enhances students' motivation [40], [41].

Context-awareness complements the motivational benefits of game-based learning by enabling situated, authentic and personalized learning experiences [42] with additional characteristics of permanency, accessibility, immediacy, interactivity, calmness, and seamlessness [18]. In the following, we give examples of combinations of games and context-awareness to deliver situated learning experiences that leverage the motivational power of games. UFractions [10] is a storytelling fraction learning game that utilizes a mobile device and wooden fraction rods. Jamiolas is a context-aware, situated learning space for studying Japanese onomatopoeia [19]. Via Mineralia uses location awareness for learning about a mineral exhibition [16]. Savannah is a location-aware game where the player learns about lions' behavior by exploring a virtual savannah acting as a lion [17]. In Heroes of Koskenniska, location-awareness, environmental sensors, and storytelling gameplay are combined to increase environmental awareness in a Finnish forest [43]. EULER combines RFID, sensors, and AR to provide context-sensitive learning content through a game in an outdoor environment for elementary school students [18]. Ambient Wood takes students to a field trip in a forest to learn about ecology by using environmental sensors for measuring light and moisture [15]. Although Ambient Wood is not a game, its affordances are related to other context-aware educational games (e.g., connecting learning content to situations, engage with the environment).

2.3 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" [44, p. 14]. Storytelling is a powerful learning tool that promotes motivation [11]. Storytelling as an instruction method has many other advantages, such as enhancing students' creativity, memory and critical thinking skills, gaining the students' attention [12] as well as helping to develop interaction among students [11].

Digital storytelling, where digital media is used to express, store and share stories, is opening up new possibilities for learning. When used in education, digital stories allow interactivity and facilitate options for non-linear storytelling [45]. Digital storytelling also promotes 21st century skills, engages teachers and students, and encompasses multiple literacy skills [46]. Hung et al. [47] 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 [39]. Storytelling has been applied in several science learning games [43], [39], [10], [48], and it has been shown that the use of digital storytelling in game-based learning can provoke intrinsic motivators such as altruism and fantasy [10].

3 The ScienceSpots AR Concept

We combine the affordances of games, context-aware learning, and AR to form a learning environment that assists learners in comprehending scientific concepts such as geometry or kinetics in an enjoyable manner. ScienceSpots AR is an Android-based platform on which context-aware storytelling games can be created. The goal of the platform is to provide a reusable learning environment to help students understand different concepts of science through interaction and experimentation with real and virtual objects.

To increase student engagement, the learning content in ScienceSpots AR 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, in turn, 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). This promotes ownership of the learning content and process, which is further strengthened by the ability to share games with other learners. Authored games are stored on the ScienceSpots AR server (Section 4.2) from where they can be searched and downloaded by the learners. The server also hosts the Web-based Learning Process Monitor (LPM) which 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.

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 meter high tree. First he climbs up to the branch at the $^3/_4$ of the tree's height. Then he descends $^1/_2$ of the tree's height. How high is Senatla now in the tree?*

Science Spot 2 could include a 3D 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, and for each AR challenge, there can be one or more AR objects floating above a target. The player solves the challenges by interacting with virtual objects or by giving an answer on the smartphone, as discussed above.

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 school yard 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.

4 THE SCIENCESPOTS AR ARCHITECTURE

ScienceSpots AR 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

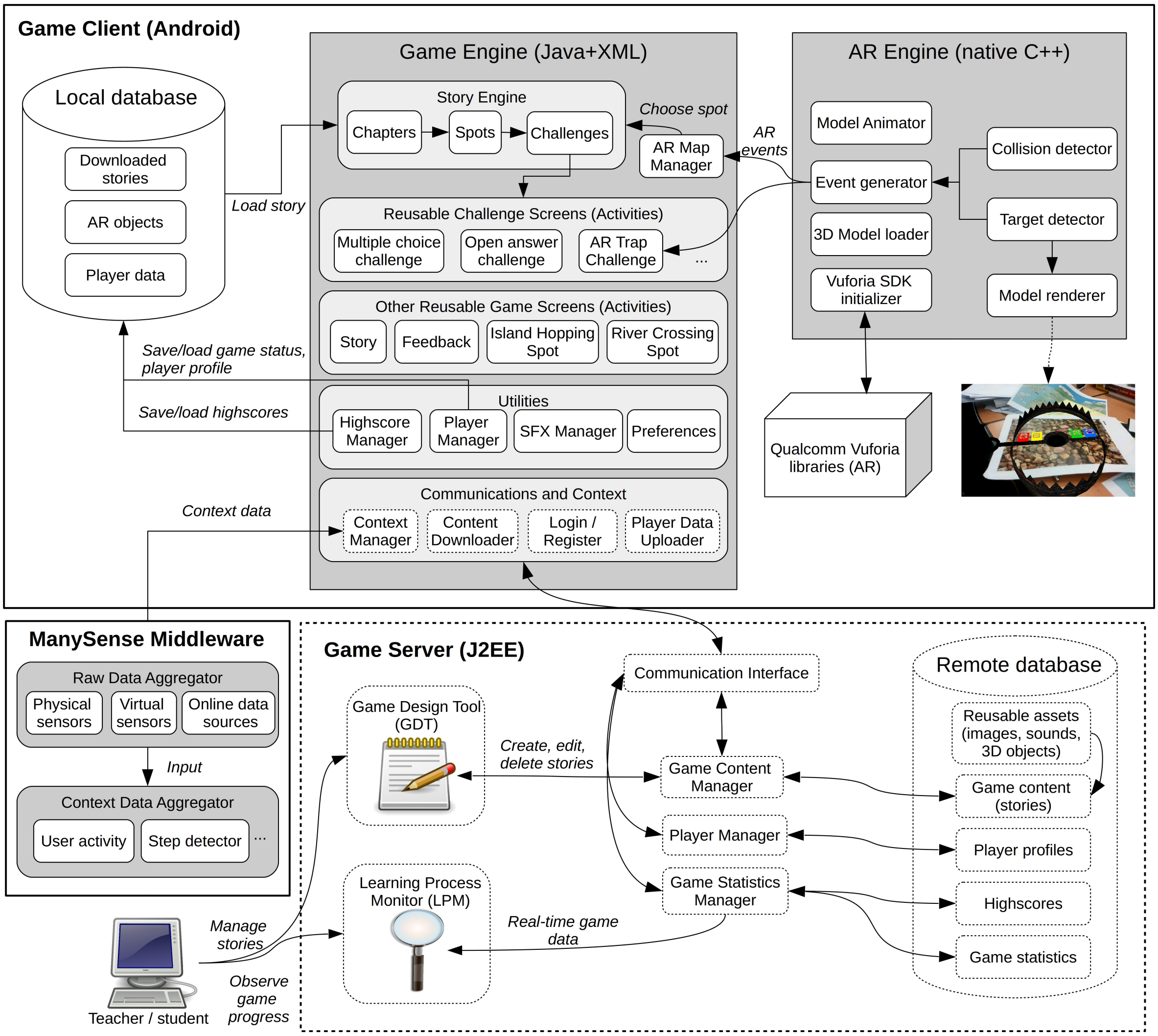

Fig. 1. Logical architecture of ScienceSpots AR

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 paragraphs, we describe the platform architecture in detail. The server module (dotted border) is currently under construction.

4.1 The Client

The ScienceSpots AR client was designed to run on Android smartphones and tablets and is divided into two parts: Game Engine and AR Engine. Game Engine contains game logic and features other than AR. Story Engine loads a game data from a local database and manages the player's progress through the game by activating the appropriate screen at each stage. It has data containers for chapters, spots, and challenges, following the logical content structure. AR Map Manager is a special component that takes care of the transitions between spots. It is triggered by Story Engine at the end of each spot to show all the available spots on an AR map.

Keeping extensibility in mind, we designed Game Engine so that it contains reusable screen templates. For example, logic of the challenge screens can be reused by simply replacing their content. Similarly, the story screen, feedback screen, and spot screens can be reused within a game or between games. Naturally, we can introduce new screen templates in the future to be reused by game creators. Reusable screens are possible due to Android's Activity-driven architecture where each screen is represented by an Activity object and switching between Activities is trivial.

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 client crashes or the player wishes to stop the game in order to 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 background music and sound

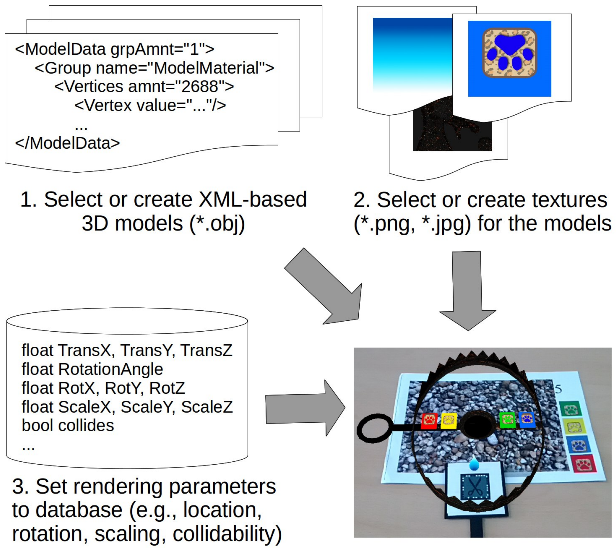

Fig. 2. Reusing AR content

effects embedded in a game. Preferences allows 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 games 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, such as target detection, rendering, animations, collision detection, and event generation. The AR features are implemented using Qualcomm's Vuforia[1] library, which uses computer vision algorithms to track different types of targets, such as image targets (i.e., any image with high details) and frame markers. Communication between AR Engine and Game Engine is realized through the observer pattern whereby Game Engine can subscribe to events such as collision starting/ending and targets entering/exiting the view. Thus, we can create custom AR challenges in Game Engine without touching the underlying AR code.

The AR content can be reused in a three-step process as shown in Figure 2. First, the geometry of a 3D model is defined in an XML-based Wavefront OBJ format, which most 3D graphics applications support. Second, a texture image file (JPG or PNG) is defined to be used as the model's "skin". Third, rendering parameters such as model location, rotation, and scale in relation to the AR target are defined. When the model is rendered by the AR engine, it uses these parameters to position the object on the target. This AR content workflow enables the reuse of the existing models and textures, which can be laborious to produce.

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

4.2 The Server

The ScienceSpots AR server, which is currently under construction, runs on a Java 2 Enterprise Edition (J2EE) application server. Communication interface is a RESTful façade that accepts incoming HTTP connections from the clients and redirects them to appropriate managers. A remote database holds the player data, media assets, and games that can be downloaded by the clients. Game Content Manager provides game data to the clients and to the Web-based Game Design Tool (GDT). Using GDT, users can create their own games by graphically arranging parametrized screen templates (i.e. Android Activities) into a directed graph and connecting any AR screens to specific locations on a map. This way, the teacher can customize game logic (e.g., challenges, story, spot screens) and content without programming. The teacher can also add or reuse media assets, such as graphics, sounds and 3D models. Table 2 exemplifies reusable assets that were created for Leometry (see Section 5). Background sounds and images are customizable in all screens. The limitations of GDT are: 1) creating screen templates requires recompilation of the client and the server, 2) only story-driven game structure is supported (but mini-games can be embedded in a story), 3) 3D models must be in OBJ format, and 4) to customize AR content, the user must have a basic understanding of 3D models.

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 areas with links to challenges, order of clicking
Island hopping spot	clickable areas with links to challenges, order of clicking
Game characters	names, posture images
Main menu	background, button images

Game Statistics Manager handles game session data observable by Learning Process Monitor (LPM). Using Android's Analytics SDK, 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.

4.3 Context-Awareness through ManySense

The potentiality of context-awareness in ScienceSpots AR lies in the ManySense middleware [49] through which challenges and other screens can become context-aware. ManySense's Raw Data Aggregator provides unified access to heterogeneous raw data sources such as sensors and Internet services. Currently supported data sources include the Android Sensor API (Application Programming Interface), Sony SmartWatch SW2, Zephyr heart-rate monitor, OpenWeatherMap API, and Myo gesture armband. New data sources can be added fairly easily through ManySense's adapter-based architecture.

ManySense's Context Data Aggregator simplifies the access to context inference algorithms that infer the details of the user's context. These algorithms, also implemented using an adapter-based architecture, receive raw data from Raw Data Aggregator, and then process it to create higher level meanings. For example, a step detection algorithm converts raw accelerometer data into steps taken by the user. Currently implemented context inference algorithms include a step detector, an activity detector (standing, walking, running), and indoor positioning using WiFi.

ManySense runs in a background service and can be accessed by other Android applications through a connection library. Game Engine's Context Manager, currently under construction, mediates communications between game screens and ManySense. When a game screen wishes to get data (raw or inferred), it makes a request to Context Manager which, in turn, sends appropriate query to ManySense and passes the return values back to the screen. Involving Context Manager as a mediator allows us to include common code specific to ScienceSpots AR, such as converting locations to spot IDs or caching data.

A game may require a deeper understanding of the learner's context than what ManySense can currently provide. Therefore, we propose the use of ontologies to model the learner's context [50]. ManySense has a server-side extension for heavy calculations, such as ontology inference. For each game instance, we envision an ontology describing the game's context (e.g., location, current players and their data, spots, challenges). These ontologies are populated automatically based on the game content and player profiles in the database. The context data acquired through players' ManySense instances are also inserted into the ontology. An inference engine (e.g., the rule-based engine in Apache Jena) can find new information from the ontology, such as who are available for a collaborative challenge, what are the next available spots, or what is the best hint level for a player.

5 Leometry

Leometry is a proof-of-concept game for demonstrating some of the features of the ScienceSpots AR concept. It aims to teach basic geometric shapes such as triangles, circles, and rectangles to 5th and 6th 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 ScienceSpots AR, and evaluated it in a Korean school environment.

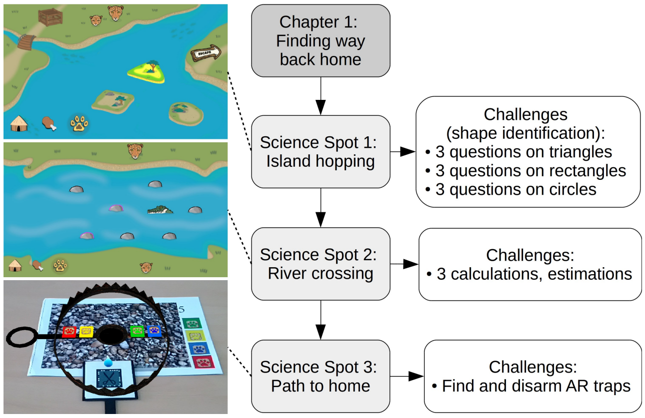

Fig. 3. Leometry story structure

Leometry uses a 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 the player 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.

Leometry development started by analyzing UFractions, an educational game which combined a mobile-based story with problem solving using physical fraction rods. UFractions provoked intrinsic motivators that are not typical in mathematics classes [10]. Table 3 lists these motivators and corresponding game features. Based on our analysis of UFractions, we established design guidelines for Leometry as follows: 1) storytelling, 2) pedagogical grounding, 3) appealing user interface with cartoonish and lighthearted drawing style, 4) challenges with scaffolding hints, 5) immediate feedback, 6) characters based on real-world examples, and 7) real world connections.

We reused the leopard characters from UFractions and wrote a story with geometry challenges. These challenges were prepared with Korean and Finnish mathematics education experts, and they were grounded on the Van Hiele model, which describes

TABLE 3
Motivators and features in UFractions

Motivator	Features
Altruism	Story
Challenge	Fraction problems, collecting points
Cognitive restlessness	Fraction problems, collecting points
Curiosity	Story, fraction problems
Fantasy	Story
Relations	Team-play, collaboration
Technology	Mobile phone, fraction rods

the process of geometry learning [51]. The game concentrates on the first two out of five van Hiele levels because the transition from one level to another is possible only if the earlier levels are accomplished. 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 to identify its properties, such as the number of sides or angles.

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.

The game was created with appealing graphics, sounds, and simple interaction techniques. Figure 4 illustrates selected game screens. Screen A shows a scrollable story with text, images, and background sound. Screens B-C exemplify game challenges based on Van Hiele levels [51]. In these challenges, the player must identify a valid shape (B) and 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 in Section 4.2.

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 5). The AR map shows available ScienceSpots 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 5). 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 [52]. Both these games utilize our AR technology, thus demonstrating its reusability.

6 EVALUATION

In order to measure conceptual feasibility of ScienceSpots AR, we evaluated Leometry with 61 (52% male, 48% female) 5^{th} 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 research design and the obtained results in detail.

6.1 Research Design

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. Research ethic requirements were met by acquiring data collection and media usage permissions. Furthermore, players' personal data such as name were not collected.

Before evaluation, the questionnaire was translated into Korean and the game client using Korean language was installed on a variety of smartphones and tablets (Samsung Galaxy Note 2, Samsung Galaxy S III, Samsung Galaxy SII Plus, Samsung Galaxy Nexus, Nexus 7, Samsung Galaxy Tab 10.1, and Samsung Galaxy Note 10.1). Data were collected from two separate classes in May 2014. Both 40-minute sessions were organized as follows: First, the researchers took 5 min to explain the purpose of this 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 when they had problems during gameplay. Figure 6 shows the players solving geometry challenges. During the remaining 20 minutes, the players filled in the questionnaire and were allowed

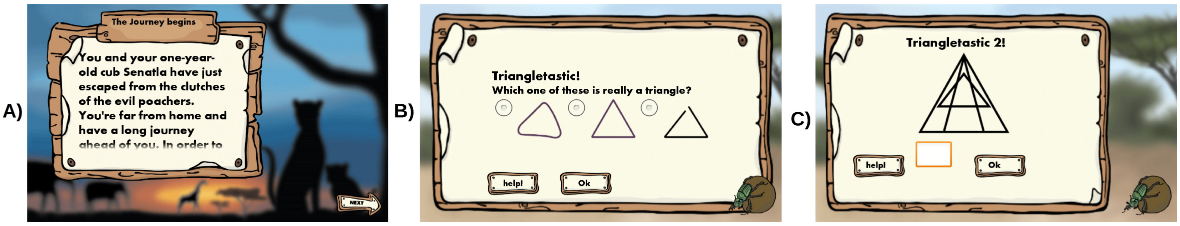

Fig. 4. Leometry screen samples

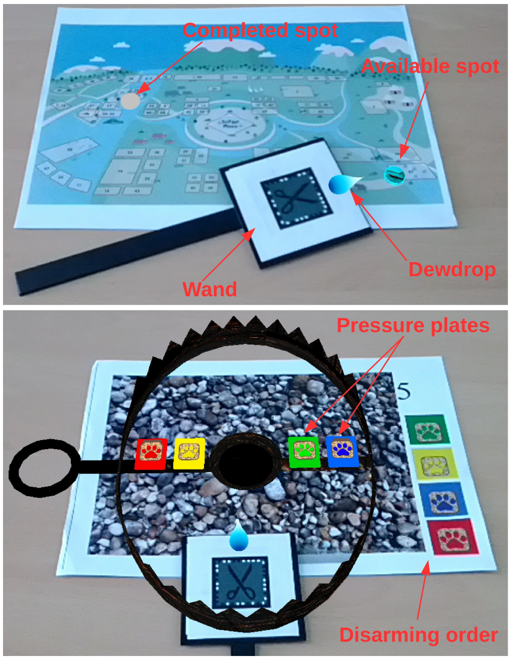

Fig. 5. The AR features of Leometry: AR map with Science Spots (top) and boss challenge (bottom)

Fig. 6. Players solving geometry challenges

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. Interviews were recorded, transcribed, and translated into English.

6.2 Results

We analyzed three aspects of ScienceSpots AR 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 percentual 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.

6.2.1 Features

We measured the reception of Leometry's features by asking "which features did you like?" Figure 7 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 [8], [36], [10]. 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*

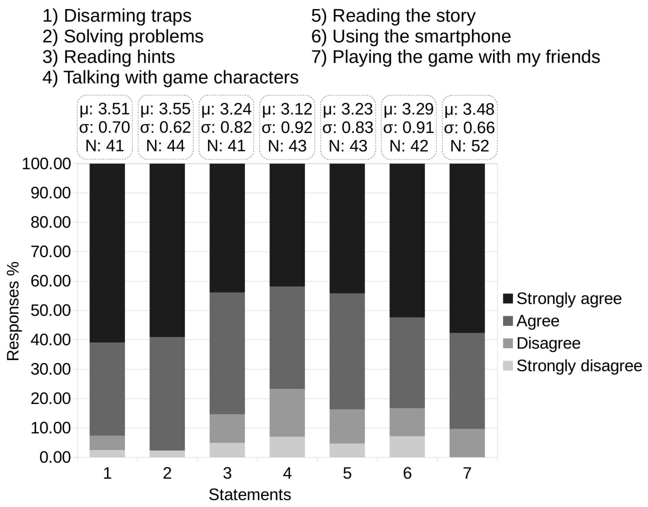

Fig. 7. Results: Features (which features did you like?)

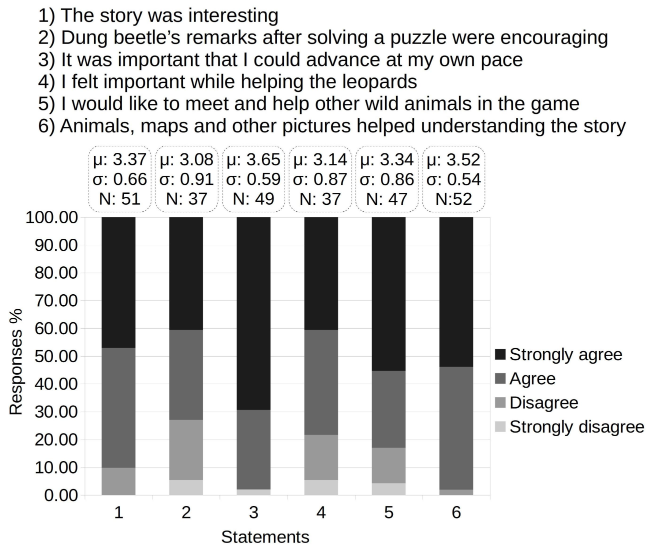

Fig. 8. Results: Storytelling approach

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)

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.

6.2.2 Storytelling approach

The reception of storytelling approach was measured by statements related to the Leometry story (Figure 8). The statements 3-5 in Figure 7 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. 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)

Statements 2 and 4 measure the effect of the story-driven feedback mechanism in the challenges and altruistic immersion in the story, respectively. A significant number of students omitted their opinions to these statements, and relatively many negative answers were given (27% and 22% for statement 2 and 4, respectively). Without further investigation, we cannot state the exact reasons for this. Regarding statement 2, some players may not have paid attention to the feedback screen if they were focused on solving the challenges quickly. One way to improve this is to include essential information in the feedback

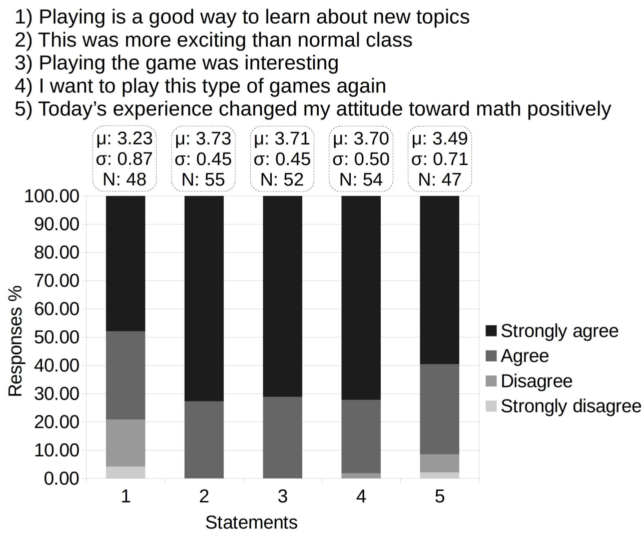

Fig. 9. Results: impact

(e.g., clue to a riddle) that encourages reading it. 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)

6.2.3 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 9 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)

By asking if the players would like to play other Leometry-like games (4), we intended to find out about ScienceSpots AR's potential as an educational gaming platform. Positive response (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.

7 Discussion

The 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 Section 2.1).

We have only studied the *conceptual feasibility* of ScienceSpots AR. Table 4 lists all feasibility dimensions that should be addressed 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 ScienceSpots AR 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, same challenges were presented to all players irrespective of their geometry skill level and this was criticized by some players. Following the concept of ScienceSpots AR, 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 ScienceSpots AR 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 ScienceSpots AR 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.

The contributions of this paper have the following limitations: First, the implementation of the ScienceSpots AR 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 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 ScienceSpots AR using existing models for mobile learning [53] and augmented reality [54].

8 Conclusion

We introduced the ScienceSpots AR concept for creating context-aware storytelling games with AR. ScienceSpots AR was designed to be extensible and portable so as to support learning across various science disciplines and contexts. To investigate its feasibility, we prototyped the ScienceSpots AR concept with a geometry learning game Leometry, and evaluated it with Korean elementary school students. The evaluation results were positive with some points for improvement. The contributions of this paper are as follows: ScienceSpots AR platform concept and architecture, design and implementation of the Leometry game, and mixed-method evaluation of Leometry.

Games on ScienceSpots AR 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, ScienceSpots AR could introduce science learning games for children around the world. Schools, parks, backyards, streets and forests could become theaters for pedagogical plays where players of different backgrounds and skills assemble to learn science in an engaging way.

ScienceSpots AR could be used in other domains as well through parametrized screen templates (e.g., story, challenges). Pedagogical efficiency of the platform stems from the learning content placed inside these templates. Due to Android's Activity framework's flexibility, in the future we can expect to see templates specifically designed for pedagogical use, such as a learning log or an experiment recorder.

Although the evaluation results indicate that the ScienceSpots AR concept is feasible from the perspectives of features, storytelling and impact, it is important to note that it was not thoroughly evaluated. Important components of the platform, such as GDT, LPM and context-awareness through ManySense, remain to be validated. Therefore, the next research steps include finishing the ScienceSpots AR 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. At the moment of writing this paper, we are polishing Leometry to be published in Google Play where it can be accessed by anyone with an Android device.

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