computers

MDPI

Article

Mobile Educational Augmented Reality Games: A Systematic Literature Review and Two Case Studies

Teemu H. Laine †

Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, 97187 Luleå, Sweden; teemu@ubilife.net; Tel.: +46-(0)910-585717
† Current address: Forskargatan 1, 931 87 Skellefteå, Sweden

Received: 31 January 2018; Accepted: 1 March 2018; Published: 3 March 2018

Abstract: Augmented reality (AR) has evolved from research projects into mainstream applications that cover diverse fields, such as entertainment, health, business, tourism and education. In particular, AR games, such as Pokémon Go, have contributed to introducing the AR technology to the general public. The proliferation of modern smartphones and tablets with large screens, cameras, and high processing power has ushered in mobile AR applications that can provide context-sensitive content to users whilst freeing them to explore the context. To avoid ambiguity, I define mobile AR as a type of AR where a mobile device (smartphone or tablet) is used to display and interact with virtual content that is overlaid on top of a real-time camera feed of the real world. Beyond being mere entertainment, AR and games have been shown to possess significant affordances for learning. Although previous research has done a decent job of reviewing research on educational AR applications, I identified a need for a comprehensive review on research related to educational mobile AR games (EMARGs). This paper explored the research landscape on EMARGs over the period 2012–2017 through a systematic literature review complemented by two case studies in which the author participated. After a comprehensive literature search and filtering, I analyzed 31 EMARGs from the perspectives of technology, pedagogy, and gaming. Moreover, I presented an analysis of 26 AR platforms that can be used to create mobile AR applications. I then discussed the results in depth and synthesized my interpretations into 13 guidelines for future EMARG developers.

Keywords: education; games; augmented reality; mobile; review; case study; augmented reality platforms

1. Introduction

The birth of augmented reality (AR) as a concept, as it is currently believed, occurred more than one hundred years ago. In 1901, Baum published a novel describing electronic see-through goggles that projected a letter onto a person's forehead indicating the persons's character [1], thus augmenting the real-world view from the spectator's perspective. In 1968, thanks to advances in computer and display technologies, the first head-mounted display with virtual and augmented reality features was developed by Sutherland [2]. Since the 1990s, technologies enabling AR have been developed for a wide range of purposes including but not limited to tourism [3], education [4], skill training [5], physical exercise [6], and the military [7]. During this millennium, head-mounted displays have increasingly given way to powerful mobile devices equipped with cameras that can create mobile AR experiences in a context-aware manner. This has led to proliferation of mobile AR applications and mobile AR software development kits (SDKs) in recent years.

In this paper, I define *mobile AR* as a type of AR where a mobile device (smartphone or tablet) is used to display and interact with virtual content, such as three-dimensional (3D) models, annotations, and videos, that are overlaid on top of a real-time camera feed of the real world. This definition of mobile AR therefore leaves out applications that show virtual content on the mobile device screen without a real-time camera feed, applications where virtual content are projected through a camera other than that of a mobile device (e.g., camera on Microsoft Kinect), or applications developed solely for devices other than mobile devices (e.g., smart glasses). For example, location-based applications created with a platform called ARLearn [8] are often referred to as AR applications, but they do not show virtual content on top of a camera feed, and are hence disqualified from inclusion in this review.

AR has been widely used for educational purposes across subject areas both in formal and informal learning settings, with several literature reviews existing on the matter (see e.g., [4,5,9–11]). This is not a surprise due to multitude of affordances that AR can provide for pedagogical scenarios [4,11–14]. Mobile AR is particularly well-suited for educational applications in informal contexts, such as museums, parks, and streets, where the learning experience can be adapted to match the location and other contextual information connected to the learner.

Although mobile AR can bring added value to practically any conceivable application area, ranging from business to medicine and from tourism to education, the area where it has gained the most popularity is gaming. Before the launch of Pokémon Go in 2016 (a location-based game where the player hunts and catches virtual monsters projected through AR), mobile AR was a concept that the general public had seldom heard of. Yet mobile AR games existed long before Pokémon Go (see e.g., [15,16]) and recently they have also been adopted for educational purposes.

In this paper, I focus on the topic of educational mobile AR games (EMARGs) because, to the best of my knowledge, they have not yet been systematically and comprehensively investigated from the pedagogical, technological, and gaming perspectives. I seek to answer the research question: "What are the technological, pedagogical, and gaming characteristics of contemporary mobile AR games in the context of education?" by conducting a systematic literature review on 31 scholarly articles describing EMARGs between the years 2012 and 2017, and by presenting two EMARG case studies in detail: Calory Battle AR, a location-based game that combines physical exercise with a possibility to include educational content, and Leometry, a story-driven geometry learning game with AR features. These case studies were selected because the author was involved in their development and evaluations, thus it is possible to describe them in depth. Moreover, I provide a review of 26 contemporary mobile AR platforms (both SDKs and non-programmatic toolkits) that can be used for creating EMARGs as well as other mobile AR systems. I then discuss the literature review results in detail, and synthesize my interpretations into 13 guidelines that future EMARG developers can utilize in their work.

2. Related Work

Pedagogical uses of AR have recently been an active topic among educational technology researchers [4,5,9–14] and a significant body of studies conducted specifically on educational mobile AR exists. In 2013, FitzGerald et al. [17] published a review on AR in the context of mobile learning where they analyzed six mobile learning systems that utilized AR as a key component. Their comparison taxonomy featured six variables, mostly focusing on non-technical aspects: device/technology, mode of interaction/learning design, method of sensory feedback, personal/shared experience, fixed/static or portable experience, and learning activities. In addition to comparing the six systems, FitzGerald et al. discussed pedagogical and technological challenges that may need to be addressed when educational mobile AR systems are used. In a more design-oriented review, Specht et al. [18] analyzed several mobile AR applications and discussed their applicability to learning. The authors proposed interaction design patterns to be combined with educational patterns when creating educational mobile AR applications, and described how various user context data can be used to contextualize the AR learning experience. Although these and other previous reviews on educational mobile AR are valuable for educational technologists, in the context this study they lack one essential aspect: gaming.

As this paper focuses on investigating contemporary educational mobile AR games, it is imperative to provide an overview of previous attempts to review them. Though the number of discovered previous EMARG reviews (see Table 1, where "n/a" stands for not available) is low and their scopes vary, they provide valuable complementary data which can especially help in deepening the understanding of pedagogical aspects of EMARGs. In their review published in 2012, Schmitz et al. [19] analyzed eight EMARGs through design patterns for mobile games. Whilst ignoring the technological aspects of the reviewed games altogether, Schmitz et al. discovered that EMARGs can have certain motivational and pedagogical effects, although the role of AR is not clear in these results. Koutromanos et al. [20] reviewed seven mobile AR games developed for informal and formal environments. Their analysis perspective was that of research design and evaluation, and the results indicated that in some cases mobile AR games, among other effects, can enhance learning whilst increasing authenticity and engagement. A recent review by Godwin-Jones et al. [21], conducted during the aftermath of the Pokémon Go craze, focused on AR in the context of second-language learning. This review is by no means comprehensive nor methodologically strong, but it provides a good overview of how AR games and other AR applications can facilitate learning of foreign languages, and what the future of second-language learning might be like with emerging technologies such as the Microsoft HoloLens. Moreover, Godwin-Jones et al. describe AR platforms that have been used for developing language learning applications. Finally, Tobar-Munoz [22] published a doctoral dissertation on the topic of AR in game-based learning, including a review of 27 educational games that utilized AR. Although not all of the reviewed games were developed for mobile devices, this review provides a complementary view of the research landscape of EMARGs, with aspects such as device type, visual display, content, feedback, and details of evaluations.

Table 1. Previous studies reviewing educational mobile augmented reality games (EMARGs).

Review	Year	Focus	# of Studies	Timespan
Schmitz et al. [19]	2012	Motivational and pedagogical effects	8	2005–2010
Koutromanos et al. [20]	2015	Research design and evaluation results	7	2000–2014
Godwin-Jones et al. [21]	2016	Uses of AR apps and games for second-language learning	n/a	2009–2016
Tobar-Munoz [22]	2017	Multiple aspects of game-based AR learning apps	27	2009–2017

My analysis of previous EMARG reviews indicated shortcomings that justify this study. Firstly, the number of analyzed games was typically low, and thus a more comprehensive and systematic review is called for. Secondly, previous reviews set little focus on the technological aspects of EMARGs. Thirdly, there is a lack of comprehensive overview of AR platforms that can be used for creating EMARGs. Thus, to fill these gaps in the academic landscape, I provide a comprehensive review of recent EMARGs with foci on pedagogical, technological and gaming aspects.

3. Methodology

A comprehensive and systematic literature review of available literature on EMARGs was conducted. In the literature review, I analyzed 31 EMARGs that were presented in peer-reviewed journals and conference articles. The articles examined were published between 2012 and 2017.

To conduct the literature review, I used a process with three stages of filtering and analysis. In the first stage, I searched articles from Google Scholar, IEEE Explore, and the ACM Digital Library over the years 2012–2017 with search phrases comprising different combinations of the terms "mobile", "augmented reality", "education", "learning", "game", "gamification", "serious game", "Android", and "iOS". I focused on EMARGs reported in academic research, and thus commercial applications available in Google Play or the Apple App Store were excluded.

I read the titles of the first 200 articles in the search results of each search engine and selected those that appeared to be relevant in terms of AR, games, and education. At this stage, I accepted studies proposing AR-based learning environments or AR platforms, and review articles. After the first stage, I had 225 studies for further analysis of which 54 contained reviews, 4 proposed AR platforms, and the remaining 167 were potential EMARG articles. It must be noted that a few articles discovered through Google Scholar were behind a paywall, and were thus inaccessible.

In the second stage, I read the abstracts of the selected 167 articles and skimmed through their content. The purpose of this stage was to pick only those articles that met the following conditions: (1) they had to propose a game with an educational purpose; (2) they had to use AR; (3) they had to be based on a mobile device (phone or tablet); and (4) they had to be implemented (e.g., not merely proposed or designed). After this stage, 44 articles remained.

In the third stage, I analyzed the 44 articles in depth, whilst creating a taxonomy of features to be used for comparing the systems. This was an iterative process: as new aspects emerged, I modified the taxonomy and revisited already analyzed articles. The same selection criteria were applied as in the second stage to filter out inapplicable systems. In total 29 EMARGs survived the scrutiny and made it to the results table, including the two case studies. Additionally, during the manuscript revision phase, two articles were added based on the suggestions from the reviewers, thus making the final set total of EMARGs 31.

The investigation of mobile AR platforms was conducted by the following approach. I defined mobile AR platforms to cover SDKs for developers as well as non-programmatic toolkits through which AR applications can be created by non-technical users. Additionally, a qualified platform must be able to support one or more mobile device platforms. First, I noted down all AR platforms that were listed in the potential EMARG articles analyzed in the third stage, as well as the AR platform articles found in the first stage. Then, I complemented these findings with more platforms discovered using Google with the search phrases "augmented reality SDK", "augmented reality platform" and "augmented reality toolkit". As a result, 42 potential mobile AR platforms were identified, and this number was reduced to 26 after I analyzed them in depth. For example, there were several platforms that did not fit to my definition of mobile AR platform, and some research-based platforms were insufficiently documented. A feature taxonomy was then iteratively created under which the key features of the analyzed mobile AR platforms were reported.

4. Results

The results of this paper are structured as follows: I first describe the results of a systematic literature review, and then present the two case studies—Calory Battle AR and Leometry—in detail.

4.1. Literature Review

Here we look into the results of my systematic literature review on articles describing EMARGs published in 2012–2017. First, an overview of the 31 discovered EMARGs is provided, followed by their approaches to pedagogy, AR, and gaming. Finally, we review AR platforms that can be used for creating educational AR games on mobile devices.

It is notable that there were several games [8,23–32] that were referred to as AR games, but that were excluded from the final results because they did not satisfy my definition of AR. These games are essentially educational location-based mobile games based on the ARIS (Augmented Reality Interactive Storytelling) [33], ARLearn [8], or FreshAiR (http://www.playfreshair.com/) platforms, but their concept of AR is merely location-awareness without virtual content being augmented on top of a real-world view. The ARIS platform, however, has recently received an update that enables camera-based AR. Despite being excluded from the final results, I have cited these games above because they might be of interest to researchers working on educational location-aware games.

4.1.1. Overview

Table 2 presents an overview with names, publication years, country codes (CCs), and short descriptions of the EMARGs that passed the criteria for data collection and analysis. If a game did not have a name, I used the authors' names instead. The country code column reports the locations of conducted experiments, or if not reported, the locations of the authors' affiliations. Articles on EMARGs have been published every year within the literature review's timespan, with the most active years being 2013 and 2016, having 7 and 8 articles, respectively. Spain (ES, 4), Republic of Korea (KR, 3), Taiwan (TW, 3), USA (US, 3), Germany (DE, 3), and Greece (GR, 3) were among the countries with the most articles published on EMARGS, and thus it can concluded that gamification of mobile AR for educational purposes is a global phenomenon in academia. Moreover, I observed that most of the reviewed games were research prototypes, thus they were not available for downloading and testing.

4.1.2. Pedagogy

In Table 3, I have summarized some of the pedagogical aspects of the reviewed EMARGs, including subjects that were taught, target learners, pedagogical context (informal or formal), and the type of evaluation conducted on each game. Here, a dash ("-") means that the study did not include the aspect (e.g., several studies did not conduct an evaluation); "n/a" is used when the aspect could not be determined due to lack of information. These notations are also used in subsequent tables presenting the results.

Table 2. Overview of EMARGs. CC: country code.

Name (Year)	CC	Description
AmonPlanet [34] (2014)	US	Learn to solve fraction problems in an story-driven AR game guided by a believable pedagogical agent.
AR Ole Cierraojos [35] (2017)	CO	A story-based AR pop-up book game for practicing reading comprehension.
AR Treasure Hunt (2012) [36]	DE, NZ	A treasure hunt quiz game for increasing energy awareness
AREEF (2016) [37]	DE	Learn environmental awareness with virtual animal characters in a multi-player underwater AR game.
ARmatika (2016) [38]	ID	Learn basic arithmetics with an AR-based math puzzle game.
ARMuseum (2013) [39]	GR	A puzzle treasure hunt game for a museum to learn about oil production process.
Astrid's spår (2012) [40]	SE	Learn about the childhood home of the children's book author Astrid Lindgren.
Calory Battle AR (2016) [6]	KR	Find and defuse virtual bombs in a fast-paced location-based treasure hunt that promotes physical exercise and learning.
Conserv-AR (2016) [41]	AU	Increase awareness towards environmental conservation through an AR-based game.
EduPARK (2017) [42]	PT	A treasure hunt AR game for a smart urban park.
Electric Agents (2014) [43]	US	Learn vocabulary by interacting with a TV show through AR and mobile device sensors.
Eleftheria et al. (2013) [44]	GR	Educational AR book with game elements to learn about science.
Furio et al. (2013) [45]	ES	Learn about different states of water, water composition and pollution through AR minigames.
Furio et al. (2013) [46]	ES	Learn about multiculturalism, tolerance and solidarity by gathering food from three continents and distributing it to poor people via minigames.
Hsu (2017) [47]	TW	Learn English through AR games in real-life contexts (task-based and self-directed)
HUNT (2015) [48]	US	A treasure hunt AR game platform that could be used for education. However, no evidence of educational use was shown.
Hwang et al. (2016) [49]	TW	Learn about butterflies in a butterfly garden via a location-aware AR board game.
Igpaw (2016) [50]	PH	Learn history in a location-based AR adventure game.
Lan (2013) [51]	SG	Learn to be a responsible pet owner in a quiz game guided by animated 3D characters.
Leometry (2016) [52]	KR	Learn geometry in a story-driven AR adventure game with puzzles.
Lin et al. (2016) [53]	TW	A puzzle game for replicating geometric shape for children with disabilities.
Luostarinmäki Adventure (2014) [54]	FI	Learn history at an open-air museum through encounters with virtual characters in a location-based AR adventure game.
Martinez Zarzuela et al. (2013) [55]	ES	Learn about different animals via an AR quiz game.
NatureAR (2017) [56]	FI	Provides information on and direct interaction with real-world objects utilizing mobile AR and natural objects as markers.
Parallel (2015) [57]	CA	Resolve a mystery using a simulator showing the true behavior of charged particles moving in electric and magnetic fields.
PasswARG (2014) [58]	CA	Crack a password in a treasure hunt with different types of puzzles presented by virtual characters.
REENACT (2014) [59]	GR, ES	Engages groups of people to learn about historical battles from the points of view of reenactors and historians using 3D, AR, and social networking features.
Secret SLQ (2012) [60]	AU	A story-based game that guides the player through a multi-level library in a treasure hunt to solve a mystery by unlocking clues with quizzes.
Table Mystery (2013) [61]	NO	Mystery-adventure game about the elements of the periodic table.
Tangram AR (2012) [62]	KR	Improves spatial reasoning skills by solving tangram puzzles in an AR game.
UniRallye (2015) [63]	DE	Improves navigation skills with an AR treasure hunt game.

Table 3. Pedagogical aspects of EMARGs.

Name	Subject	Learners	Formal/Informal	Evaluation (N)
AmonPlanet [34]	Fractions	Grades 7–9	Informal (any)	-
AR Ole Cierraojos [35]	Reading comprehension	Grades 3–6	Formal	Mixed-method (16)
AR Treasure Hunt [36]	Energy awareness	n/a	Informal (any)	Qualitative (n/a)
AREEF [37]	Environmental awareness	Grades 1–6	Informal (swimming pool)	Mixed-method (36)
ARmatika [38]	Arithmetics	Grades 1–6	Formal	Quantitative (30)
ARMuseum [39]	Oil production	Grades 4–6	Informal (museum)	-
Astrid's spår [40]	Culture	Lifelong learners	Informal (museum)	Qualitative (20)
Calory Battle AR [6]	Physical exercise/any	Grades 1–9	Informal (outdoors)	Mixed-method (61)
Conserv-AR [41]	Environment conservation	n/a	Informal (nature)	-
EduPARK [42]	Any	Grades 3–7	Informal (park)	Mixed-method (74)
Electric Agents [43]	Literacy (vocabulary)	Grades K-4	Informal (livingroom)	Qualitative (34)
Eleftheria et al. [44]	Science	Grades 4–6	Formal/Informal	-
Furio et al. [45]	Water cycle	Grades 2–4	Formal	Mixed-method (79)
Furio et al. [46]	Diversity, tolerance, solidarity	Grades 2–4	Formal	Mixed-method (84)
Hsu [47]	English	Grade 3	Formal	Quantitative (38)
HUNT [48]	n/a	n/a	Informal (any)	-
Hwang et al. [49]	Ecology	Grade 5	Informal (butterfly garden)	Quantitative (57)
Igpaw [50]	History	Lifelong	Informal (city)	-
Lan [51]	Pet ownership	Grades 1–6	Informal (any)	-
Leometry [52]	Geometry	Grades 5–6	Informal (any)	Mixed-method (29)
Lin et al. [53]	Geometry	Grades 1–6	Formal	Mixed-method (21)
Luostarinmäki Adventure [54]	History	Lifelong	Informal (museum)	Mixed-method (56)
Martinez Zarzuela et al. [55]	Animals	n/a	Informal (any)	Qualitative (5)
NatureAR [56]	Biology	Grades K-6	Informal (nature)	Qualitative (11)
Parallel [57]	Electromagnetism	Higher education	Formal	Qualitative (150)
PasswARG [58]	Any	Any	Formal/Informal	Quantitative (55)
REENACT [59]	History	Lifelong	Informal (cultural center)	Mixex-method (61)
Secret SLQ [60]	Library education	Grades 2–8	Informal (library)	Qualitative (7)
Table Mystery [61]	Chemistry	Grades 5–7	Informal (science center)	Qualitative (9)
Tangram AR [62]	Spatial reasoning	Grades 1–6	Formal	-
UniRallye [63]	Navigation	Higher education	Informal (university campus)	Mixed-method (30)

The reviewed EMARGs were created for a wide range of pedagogical purposes. Mathematics was the most popular subject, including elementary areas such as fractions [34], geometry [52,53] and arithmetics [38]. Topics related to science were also popular, including physics [57], chemistry [61], lab experimentation [44], environment [37,41], and other biological sciences [45,49,55,56]. Four of the reviewed EMARGs [6,42,48,58] aimed to be general-purpose educational tools for learning any topics. Some of the games have rather shallow pedogogical content without connections to curricula. For example, Lan et al.'s [51] EMARG aims to teach children to be responsible pet owners through a simple animal ownership simulation. In another example, HUNT [48] is an AR treasure hunt game that is suggested to be used for educational purposes, but the authors do not show any pedagogical content implementation. Most EMARGs were created for primary school children, to be used in informal pedagogical settings, such as in science centers [61], libraries [60], in nature [41,49,56] or in museums [39,40], thus demonstrating how augmented content can enrich situated learning [64] experiences in authentic contexts. A few games targeted at higher education [57,63] or lifelong learners (i.e., any age group) [50,54,59]. The EMARGS that are marked as having formal contexts were created for and evaluated in classroom environments; however, many of them are context-independent and therefore can be played in anywhere (e.g., at home).

It is notable that only a few studies described the theoretical underpinnings upon which their respective learning experiences were designed. Apart from the obvious game-based learning and technology-enhanced learning that affect all EMARGs, the theories that were explicitly mentioned in varying detail were: active learning [34], contextual learning (including embedded, situated and authentic) [34–36,42], discovery-based learning [36], collaborative learning [35,43], experiential learning [41,45,46], scaffolded learning [43], the flow state [44,47], learning styles [45–47], task-based and self-directed learning [47], Van Hiele levels of geometry learning [52], problem solving [53], and independent learning [53].

With some exceptions, the reviewed EMARGs were evaluated in some way. Based on my analysis, most authors conducted a formative evaluation [65] that aims to inform further development and validation of a technology. Indeed, most of the reviewed EMARGs were prototypes and therefore the use of formative evaluation is justified. The numbers of participants (N) as well as the types of evaluation varied a lot, thus making it hard to compare the outcomes of the evaluations. One must be aware that the studies that did not report any evaluation results (or otherwise lacked information on the evaluation) [34,39,41,44,48,50,51,62] may have EMARG implementations that are incomplete or under development.

I would like to highlight two EMARGs that caught my attention with their innovativeness. An unusual game context was utilized in AREEF [37], where the players use water-proof tablets to learn about environmental awareness by playing the game in a swimming pool. Although the justification for placing the game in an underwater environment is arguable, this game concept could be refined into a marine life exploration game whilst scuba diving, or it could be used to combine physical education with any pedagogical topic, akin to Calory Battle AR [6]. As another example, Electric Agents [43] is a game with innovative combination of a television show and a mobile AR game. In this game, the players practice vocabulary by catching virtual words in AR, and throwing them back at the television set using gesture detection based on the mobile device's sensors. Electric Agents is a great example of how traditional media can be combined with AR to produce immersive learning experiences.

4.1.3. Augmented Reality

AR was implemented and used in different ways, as Table 4 illustrates. The depth of AR usage also varied and in a few cases AR was used only as a small part of a larger game or the AR use was unclear. For example, REENACT [59], where a group of players re-enact a historical event, included ZonesNavigator, a tool based on AR which allowed the player to navigate among game zones. In Secret SLQ [60], AR was reportedly used to present a historical view of the library where the game was played.

As in the last example, the article describing AmonPlanet [34] focused on design and pedagogical aspects of the game, thus I was not able to extract all information related to AR.

The *AR platform* column explains which SDK or non-programmatic toolkit was used to implement the game's AR features. Eight EMARGs have "n/a" in this column; this could mean that these studies either did not describe the used AR platform or the developers created AR features from scratch. Among those studies where a platform was mentioned, Vuforia SDK was the most popular with 12 occurrences, and 8 of these used Vuforia SDK through the Unity 3D game engine. ARToolkit (and its derivatives ARToolkitPlus and AndAR) and Metaio AR (later purchased by Apple and rebranded as ARKit) were used in 4 and 3 EMARGs, respectively. Other platforms, albeit potentially capable, were only used marginally.

The *target recognition* column lists techniques that were used to identify targets (e.g., markers, objects) on which AR content was rendered. Markers detected by the mobile device's camera were clearly the most popular targets with 24 EMARGs utilizing them. Two types of markers were found: (1) fiducial markers (6 occurrences) that represent well-defined, typically black-and-white patterns (e.g., a barcode); and (2) image-based markers (17 occurrences), which can be of any image having adequate features (e.g., sufficient detail). It is noteworthy that image-based tracking works also with fiducials. In two cases, the type of marker was undefined [36,60]. Object recognition, which is typically much harder to do than image recognition, was used in two EMARGs: NatureAR used plants attached to a cardboard [56], and in HUNT any object that has been photographed is applicable [48]. Position-based target tracking was utilized in Luostarinmäki Adventure [54] through the ALVAR AR library with an advanced point cloud technique where the camera view is compared against a previously recorded 3D point cloud of the environment, thus establishing an estimation of the camera's 3D position. Another example of position-based target tracking implementation is Electric Agents [43], where built-in sensors were used to recognize the mobile device's position, thus enabling appropriate placement of AR content.

Interaction refers to methods through which the user can interact with AR content, but excluding interactions with non-AR game components. Visual interaction means simple visualization of AR content and it was used in all EMARGs. After all, visualization of virtual content is a key component of AR. My analysis revealed that eight studies used visualization as the only interaction method. It is possible that these EMARGs used for example touch screens to allow players to interact with AR content; however, I was not able to check this because the games could not be accessed for testing. The touch screen was the second most common interaction method with 18 occurrences, which is not a surprise given that all these games were running on modern smartphones or tablets. Device sensors, typically inertial sensors, were used in a few cases to allow gesture-based interaction. For example, in the underwater AREEF game, the player interacts with AR content by tilting the device [37], and in Electric Agents, the player "throws" AR vocabulary balls back at the television set using the smartphone accelerometer [43]. The marker manipulation interaction method refers to physical manipulation of a marker in the camera view. For example, in Calory Battle AR [6] and Leometry [52], the player disarms a virtual bomb and a virtual trap, respectively, by poking a 3D bomb/trap object standing on a marker with a disarming tool represented by a 3D object on another marker. In ARMuseum [39], the player can use their hand to press a virtual button standing on a marker.

The *content types* column describes the types of visual content that were communicated to the player through AR. Three-dimensional models were the most common content type with 23 occurrences, thus demonstrating graphics rendering capabilities of modern smartphones. In total 11 EMARGs used two-dimensional (2D) content, which in my categorization refers to 2D images. Annotating virtual or real world objects with short labels or longer texts was done in 12 EMARGs, and 14 EMARGs utilized animation effects on their graphical content. It is noteworthy that the listed content types are those that I was able to identify based on figures and descriptions in the reviewed articles, thus some games may have additional unreported content types. For example, EMARGs that used 3D models may have had animations in them, but I could not always confirm that.

Table 4. AR aspects of EMARGs. SDK: software development kit.

Name	AR Platform	Target Recognition	Interaction	Content Types
AmonPlanet [34]	n/a	n/a	Visual, touch screen	3D, animations
AR Ole Cierraojos [35]	n/a	Markers (image)	Visual, touch screen	3D, 2D, annotations, animations
AR Treasure Hunt [36]	AndAR	Markers (n/a)	Visual	3D
AREEF [37]	Vuforia SDK on Unity 3D	Markers (image)	Visual, touch screen, sensors	3D, animations
ARmatika [38]	n/a	Markers (image)	Visual, touch screen	3D, annotations
ARMuseum [39]	n/a	Markers (image)	Visual, marker manipulation	3D, animations
Astrid's spår [40]	ARToolkit	Markers (fiducial)	Visual	3D, 2D, video
Calory Battle AR [6]	Vuforia SDK	Markers (image)	Visual, marker manipulation	3D, 2D, annotations, animations
Conserv-AR [41]	Vuforia SDK	Markers (image)	Visual	3D, annotations
EduPARK [42]	Vuforia SDK on Unity 3D	Markers (image)	Visual, touch screen	3D, 2D, annotations
Electric Agents [43]	n/a	Position (sensors)	Visual, sensors	2D, animations, annotations
Eleftheria et al. [44]	Vuforia SDK on Unity 3D	Markers (image)	Visual	3D, animations
Furio et al. [45]	ARToolkitPlus	Markers (fiducial)	Visual, touch screen, sensors	3D, animations
Furio et al. [46]	ARToolkitPlus	Markers (fiducial)	Visual, touch screen, sensors	3D, animations
Hsu [47]	n/a	Markers (image)	Visual, touch screen	Annotations
HUNT [48]	Metaio AR	Objects	Visual, touch screen	2D, video
Hwang et al. [49]	n/a	Markers (fiducial)	Visual, touch screen	2D, annotations
Igpaw [50]	Vuforia SDK on Unity 3D	Markers (image), sensors	Visual, touch screen	3D, annotations
Lan [51]	Vuforia SDK	Markers (image)	Visual	3D, animations, annotations
Leometry [52]	Vuforia SDK on Unity 3D	Markers (image)	Visual, marker manipulation	3D
Lin et al. [53]	Aurasma	Markers (image)	Visual	2D, video
Luostarinmäki Adventure [54]	ALVAR on Unity 3D	Position (point cloud)	Visual, touch screen	3D, animations, annotations
Martinez Zarzuela et al. [55]	Vuforia SDK on Unity 3D	Markers (image)	Visual, touch screen	3D, annotations
NatureAR [56]	Vuforia SDK on Unity 3D	Objects	Visual, touch screen	3D, animations
Parallel [57]	n/a	Markers (image)	Visual, touch screen	3D, animations
PasswARG [58]	Layar	n/a	Visual, touch screen	2D, annotations
REENACT [59]	Metaio AR	Markers (fiducial)	Visual	3D, annotations
Secret SLQ [60]	n/a	Markers (n/a)	Visual, touch screen	2D, annotations
Table Mystery [61]	Metaio AR	Markers (image)	Visual, touch screen	3D
Tangram AR [62]	Vuforia SDK on Unity 3D	Markers (image)	Visual, touch screen	3D
UniRallye [63]	Vuforia SDK	Markers (fiducial)	Visual	2D

I discovered that six EMARGs provided content authoring methods with which educators can create learning content independently without much programming experience. Additionally, some EMARGs were based on commercial AR toolkits (e.g., Aurasma, Layar) that contain content authoring tools; I have excluded their descriptions from this paragraph. Calory Battle AR [6], HUNT [48], and PasswARG [58] provided web-based editors whereby new game challenges can be created and placed on a geographical map. Created game maps/levels are then delivered to the client devices over the internet. Hwang et al. [49] mention a "learning management mechanism" that can be used by the teacher to create game content and to manage player accounts; however, neither details nor a proof of an implementation were given. Finally, Conserv-AR [41] and Martinez Zarzuela et al. [55] allowed new content to be created via editing text-based configuration files, which may require more technical skill than the aforementioned web-based methods.

4.1.4. Gaming

Table 5 presents the results on how gaming aspects have been realized in the reviewed EMARGs, including game genres, game modes, gameplay elements, and platforms on which the games were deployed. As with previous results, these results are not fully comprehensive because the information available in some of the articles was limited.

Puzzles (including also quizzes) and treasure hunting were used in 19 and 16 EMARGs, respectively, thus making them the dominating game genres. Treasure hunt games typically involved searching for AR markers (i.e., treasures) in a physical environment and presenting various game content once a marker has been found and activated through the mobile device's camera. In puzzle games, the player solves challenges by selecting a correct option or forming a pattern. In Tangram AR, for example, the player must solve a virtual tangram puzzle by selecting puzzle pieces and arranging them into a desired shape [62]. The story-driven adventure genre was used in a few EMARGs, and some of these provided a game world that spanned across a virtual world and the real world. For example, in the Luostarinmäki Adventure, the player experiences adventures through a living museum whilst conversing with virtual characters from the past [54]. Action games, which are popular among commercial games (e.g., first-person shooters), were quite rare in the analysis results. The only game that was primarily of the action genre was Electric Agents [43], where the player captures words in AR and throws them back at a television. Although AREEF [37] is primarily a treasure hunt game, it has some action game tendencies, such as destroying virtual trash objects and opening a wooden chest by tilting the device.

Game modes were categorized using the following mutually inclusive labels: single-player (SP), multi-player (MP), cooperative (Coop), and competitive (Comp). By single-player, which was the most common game mode with 22 instances, I refer to a game mode whereby players operate the game individually without having to interact with other players to advance in the game. This, however, does not rule out competition. For example, there were several competitive single-player games that were played alone, but achievements (e.g., points) were shared and compared against those of other players [37,38,49,60,63]. Most multi-player games were cooperative and some had competitive features as well. For example, in Table Mystery [61] and in REENACT [59] a team of players had different roles through which cooperation was achieved, but these games were not competitive. Multi-player mode with competition and cooperation was implemented in AR Treasure Hunt [36], Calory Battle AR [6], and EduPARK [42] where players worked together in teams whilst competing against other teams.

Table 5. Gaming aspects of EMARGs. SP: single-player; MP: multi-player; Coop: cooperative; Comp: competitive.

Name	Genre	Mode	Gameplay	Platform
AmonPlanet [34]	Puzzle	SP	Match, select, create	Phones (Android)
AR Ole Cierraojos [35]	Puzzle	SP	Match, select	Phones, tablets (Android)
AR Treasure Hunt [36]	Treasure hunt, puzzle	MP, Coop, Comp	Match, move, select, manage	Phones (Android)
AREEF [37]	Treasure hunt, action	SP, Comp	Match, select, destroy	Tablets (Android)
ARmatika [38]	Puzzle	SP, Comp	Match, move, manage, select, shoot, destroy	Phones (Android)
ARMuseum [39]	Treasure hunt, puzzle	SP	Match, move, select	Tablets (Android)
Astrid's spår [40]	Treasure hunt	SP	Match, move	Phones (iOS)
Calory Battle AR [6]	Treasure hunt	MP, Coop, Comp	Match, move, select, destroy	Phones and tablets (Android)
Conserv-AR [41]	Treasure hunt	SP	Match, move, select	Phones (Android) and smart glasses
EduPARK [42]	Treasure hunt, puzzle	MP, Coop, Comp	Match, move, select	Phones and tablets (Android)
Electric Agents [43]	Action	MP, Coop	Match, move, shoot, select	Phones (Maemo)
Eleftheria et al. [44]	Simulation, puzzle	SP	Match, select, manage	Phones and tablets
Furio et al. [45]	Treasure hunt	SP	Match, move, select	Phones (iOS), tablets (Windows 7)
Furio et al. [46]	Treasure hunt	MP, Coop	Match, move, select, manage	Phones (iOS)
Hsu [47]	Puzzle	SP	Match, select	Tablets
HUNT [48]	Treasure hunt	SP	Match, move	Phones (iOS)
Hwang et al. [49]	Board game, puzzle	SP, Comp	Match, move, select, random, shoot	Phones
Igpaw [50]	Treasure hunt, adventure	SP	Match, move, select	Phones (Android)
Lan [51]	Puzzle	SP	Match, select	Phones (Android, iOS)
Leometry [52]	Adventure, puzzle	MP, Coop	Match, move, select, destroy	Phones and tablets (Android)
Lin et al. [53]	Puzzle	SP	Match	Phones and tablets (Android, iOS)
Luostarinmäki Adventure [54]	Treasure hunt, adventure	SP	Match, move, select, manage	Tablets (iOS)
Martinez Zarzuela et al. [55]	Puzzle	SP	Match, select	Phones and tablets (Android, iOS)
NatureAR [56]	Treasure hunt, puzzle	SP	Match, move, select	Tablets (Android)
Parallel [57]	Puzzle, simulation	SP	Match, destroy, select	Tablets (iOS)
PasswARG [58]	Treasure hunt, puzzle	MP, Coop	Match, move, select, write	Phones and tablets (Android, iOS)
REENACT [59]	Puzzle, simulation, role-playing	MP, Coop	Match, move, select, shoot, avoid, write	Tablets (Android)
Secret SLQ [60]	Treasure hunt, adventure	SP, Comp	Match, move, select	Phones and tablets (iOS)
Table Mystery [61]	Puzzle, adventure, role-playing	MP, Coop	Match, select, write	Tablets (iOS)
Tangram AR [62]	Puzzle	SP	Match, move, select	Tablets (iOS)
UniRallye [63]	Treasure hunt	SP, Comp	Match, move, select	Phones (Android)

I categorized gameplay elements of the reviewed EMARGs based on the Game Bricks model that describes 10 elementary components, or "bricks", that can be combined to describe the gameplay of a videogame [66] (Table 6). The more of these elements the game uses, the more versatile it is. It is noteworthy that this classification model does not consider multi-player aspects of a game. The Match, Select and Move bricks were by far the most common bricks with 31, 28, and 20 occurrences, respectively. The existence of Match in all EMARGs can be explained by the nature of AR target tracking: players had to match the correct AR marker (or location) to proceed in the game. Yet several other uses of Match were found as well: match a pattern [6,53], symbols [45], words [43], and movement [37,43]. The Select brick was typically involved in choosing an answer to a question/puzzle, and movement appeared naturally in location-based EMARGs. Some games provided additional means of gameplay, such as: managing virtual items [44,54], a virtual environment [36] or health [38]; shooting targets [38,43,49,59]; destroying game objects [6,37,38,52,57]; avoiding an unfavorable situation [59]; and using randomness in casting dice [49]. Only in one game were the players able to use their creativity to create something new by taking photographs [34].

Table 6. The Game Bricks model [66].

Game Brick	Explanation
Avoid	Avoid or evade obstacles or enemies in the game (e.g., stay away from harmful locations)
Manage	Collect and maintain resources to reach a target (e.g., collect coins to make in-game purchases)
Random	Game events that are based on luck (e.g., throw dice)
Shoot	Shoot or throw a projectile or a hit at a target (e.g., fire a gun at an enemy)
Create	Construct new elements in the game using creativity (e.g., build a city)
Destroy	Destroy game elements or enemies (e.g., squash an enemy by jumping on it)
Match	Match a value with a target (e.g., jigsaw puzzle)
Write	Write an alphanumeric string as an input (e.g., fill-the-gaps quiz)
Move	Move physically or instruct an avatar to move (e.g., traverse between two locations in a location-based game)
Select	Select or choose an element (e.g., select a choice in a multiple-choice quiz)

To identify the target platforms of the reviewed EMARGs, I used the information available in the articles. As per my definition of mobile devices, the game platforms were categorized into phones (21) and tablets (18). Conserv-AR also utilized smart glasses together with a smartphone [41]. Although a few articles did not specify what operating system was used, the most popular operating systems were Android (16) and iOS (13), which should not come as a surprise given their dominant market shares today. Some games [45,51,53,55,58,60] were reported to be available on multiple operating systems but it is unsure how well they were tested across platforms. More exotic operating systems were represented by Electric Agents with Maemo Linux [43] and Furio et al. [45] with Windows 7.

4.1.5. AR Platforms

The current popularity of mobile AR applications is reflected in a great variety of platforms on with which mobile AR games and other applications can be created, thus providing developers with plenty of options to choose from. Table 7 summarizes 26 of such platforms with their names, target mobile platforms, availability of SDKs, methods of AR target tracking, and license information. I excluded several platforms that were not targeting at mobile devices and platforms lacking adequate descriptions. Moreover, Metaio AR, which was used in some of the EMARGs, has since been replaced by Apple's ARKit. Table A1 in Appendix A contains links to the websites hosting further information of the reviewed AR platforms.

Table 7. Mobile AR platforms.

Name	Client Type	SDK	Target Tracking	License
ALVAR	Android, iOS, Windows, Linux, Mac	Y (C++, Unity)	Fiducial, image, point cloud	Commercial
ANDAR	Android	Y (Java)	Fiducial, image	Open source
ARCore	Android	Y (Java, C#, C++, Unity, Unreal)	Sensor, object	Commercial (free)
ARIS	iOS	N	Fiducial, image	Open source
ARKit	iOS	Y (Objective-C, Swift, Unity, Unreal)	Sensor, face	Commercial (free)
ARToolkit	Android, iOS, Mac, Linux	Y (C/C++, Java, Unity)	Fiducial, image	Open source
Augment	Android, iOS, web browser	Y (Java, Objective-C, Swift, JavaScript)	Fiducial, sensor	Commercial
Aurasma	Android, iOS	Y	Image	Commercial (free)
Blibbar	Android, iOS	Y (JavaScript)	Image	Commercial (free)
CraftAR	Android, iOS	Y (Java, Objective-C, JavaScript, C#, Unity)	Image	Commercial (free)
DroidAR	Android	Y (Java)	Fiducial, sensor, location	Open source
EasyAR	Android, iOS, Windows, Mac	Y (C/C++, Java, Swift, Objective-C, C#, Unity)	Image, object	Commercial (free)
EON Reality	Android, iOS, smart glasses	Y (C++)	Fiducial, image	Commercial
Hoppala Augmentation	Android, iOS	N	Image, location, object	n/a
Infinity AR	Android, iOS, wearables	n/a	Image	Commercial
Kudan AR SDK	Android, iOS, Windows, Mac	Y (Java, C#, Objective-C, Unity)	Image, object	Commercial (free)
Layar	Android, iOS, Blackberry	Y (Java, Objective-C)	Image	Commercial
Maxst AR SDK	Android, iOS, Windows, Mac	Y (C#, Unity)	Fiducial, image, sensor	Commercial (free)
NyARToolkit	Android, iOS, Mac, Linux, Windows	Y (C/C++, Java, C#, ActionScript, Unity)	Fiducial, image	Open source
Rajawali	Android	Y (Java)	Fiducial, image	Open source
Rox AR SDK	Android, iOS, Windows, Linux	Y (C, C#, Unity)	Object, image	Commercial (free)
ViewAR	Android, iOS, Windows, web browser	Y (HTML, JavaScript, CSS)	Image, object	Commercial
Void AR	Android, iOS, Windows, Mac	Y (C#, Unity)	Image	Commercial (free)
Vuforia SDK	Android, iOS, Windows	Y (C#, JavaScript, C++, Java, Unity)	Fiducial, image, object	Commercial (free)
Wikitude	iOS, Android, smart glasses	Y (Java, Javascript, Objective-C, Unity)	Location, object	Commercial
Xzimg	Android, iOS, Windows, web browser	Y (C#, Unity)	Fiducial, face	Commercial (free)

Most AR platforms were found to support multiple client types, with Android (24) and iOS (22) being the most common cases. Some platforms also support clients running Windows (10), Mac (7) or Linux (4). To write AR programs for these clients, most platforms provide an SDK with a variety of supported programming languages, thus providing the programmer with a choice to select their preferred language. Some platforms, such as Hoppala Augmentation and ARIS, do not have an SDK but instead they present the user with a web-based editor through which content can be created without programming. Similar programming-free content editors are also provided by Augment, Aurasma, Blibbar, EON reality, and Layar.

One feature that is particularly important for game developers is how well the AR platform is integrated into existing game engines. The SDK column of Table 7 lists integrations into two popular game engines: Unity 3D (14) and Unreal (2). Through these integrations, game developers can conveniently add AR features to their games with relatively little effort. Another important observation regarding integration is that several AR platforms were found to be based on other platforms. For example, ANDAR and NyARToolkit are derivatives of ARToolkit, and ARIS, EON Reality, and Rajawali were created on Vuforia SDK, which was the most popular AR platform in the reviewed EMARGs (Table 4). Additionally, DroidAR was described to utilize OpenCV, an open source machine vision library that can be used to implement AR at a low level. Although not explicitly specified, it is possible that some other AR platforms might also have foundations in other platforms, such as Open CV or Vuforia SDK.

Several AR target tracking methods are supported in the reviewed AR platforms. Marker-based approaches are prevalent, with fiducial markers and image markers being supported in 12 and 20 platforms, respectively. Eight platforms are able to recognize real-world objects and two platforms (Xzimg, ARKit) have the ability to track the user's face. Sensor-based tracking (e.g., inertial sensors) was found to be used in ARCore, ARKit, Augment, DroidAR, and Maxst AR SDK. ALVAR was the only platform that supports tracking based on a point cloud created from the environment.

I divided licenses into open source (6) and commercial (19) groups, and further indicated with the "free" label when a commercial platform provided a free version for personal or educational purposes. These free versions of commercial platforms are often limited but can be sufficient for creating non-commercial educational applications. An interesting observation is that most open source tools support only marker-based (fiducial, image) tracking, with the exception of DroidAR.

4.2. Case Studies

Now that we have reviewed the landscape of state-of-the-art research on mobile AR games for education, we will explore two such games in detail. I participated in the development and evaluation of both of the following games, thus enabling in-depth presentation and analysis.

4.2.1. Calory Battle AR

Calory Battle AR is a fast-paced treasure hunt AR game that aims to promote physical activity among children and has also some pedagogical features. The game's story is about the Dews and the Caloroids—the good guys and the bad guys. The Dews extract energy from the players' sweat and use that energy to cast spells that make players' bodies healthier and minds sharper. In contrast, the Caloroids hate sweat and love calories, and they have deployed virtual "calory bombs" —depicted in AR on printed image targets—around a real-world context. The player's task is help the Dews to find and defuse the bombs before the allocated time runs out. Other content, such as educational quizzes, can be used in addition to virtual bombs. The detailed design process and the results of an experiment conducted in the Republic of Korea are reported in [6].

The player controls the game using an app on a smartphone and the Multitool (Figure 1). At start, the game shows a map with a timer, bomb locations and the player's current location. The player then runs to one of the targets, starts the Analyzer to see an animated virtual bomb, and defuses it by touching the fuses with the Multitool. The fuses have pictures of unhealthy food such as pizzas and hamburgers. The Multitool can be used for different types of interactions with AR content; here it is used to remove bomb fuses in the correct order. Although Calory Battle AR can be played individually, it is best played as a team of two players where one player operates the phone and the other player uses the Multitool to defuse the bomb (Figure 2). After the game ends, the teams can compare their points on a leaderboard website.

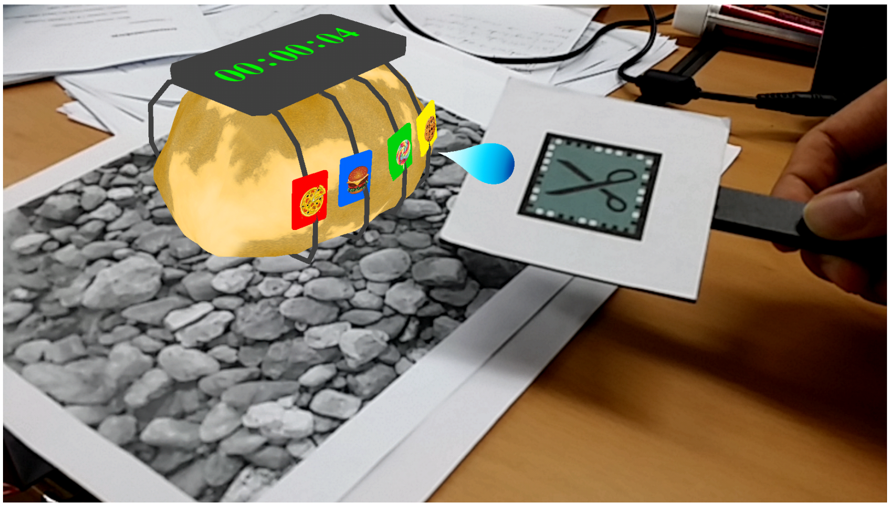

Figure 1. Virtual bomb and the Multitool in Calory Battle AR.

Figure 2. A team of players defusing a bomb.

The game can be easily deployed at different locations because it does not require any special equipment other than the game app on an Android smartphone and printed image targets representing AR content. The game has a web-based editor for creating and sharing game maps. Available game maps can be browsed, searched and downloaded to the smartphone using the map manager feature. The game's AR functionality is implemented using Vuforia SDK with a simple game engine through which 3D and 2D content can be animated and manipulated. The game's user interface and the web-based map editor are illustrated in Figure 3 where (A) is the main menu; (B) is the map screen with a selected bomb task—other tasks such as quizzes have different icons; (C) is the map manager for searching and downloading game maps; and (D) is a web-based map editor with a new "calory" bomb task.

Ultimately, Calory Battle AR aims to persuade players to change their perceptions and motivations regarding physical exercise, thus it can be referred to as a *persuasive game* [67]. The game's story emphasizes the importance of being physically active and implicitly teaches the player that calorie intake and expenditure should be balanced. More pedagogical aspects can be embedded in the game through additional activities. For example, the bomb defusing activity can be complemented with pedagogical quizzes, minigames, and location-sensitive learning materials—much like in many of the treasure hunts in Table 3. Moreover, the game also encourages players to train their navigation skills.

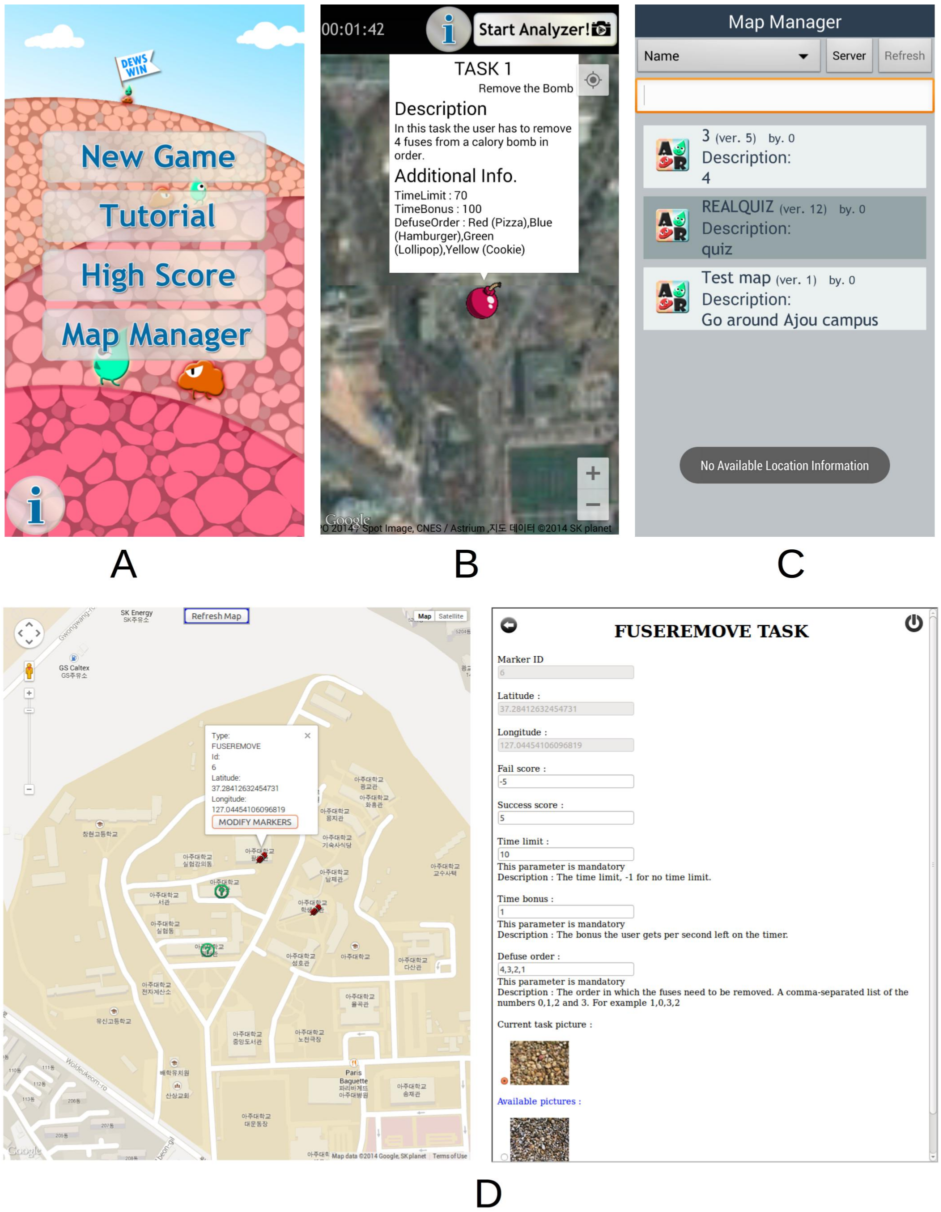

Figure 3. Calory Battle AR user interface and the web-based map editor.

4.2.2. Leometry

Leometry (a portmanteau of "leopard" and "geometry") aims to teach basic geometric shapes to elementary school students. The game uses a story as a vehicle to immerse players in an adventure on the African savannah. The story begins when a mother leopard and her cub escape from poachers who have captured them, and the player is asked to help the leopards get back home. The road is filled with obstacles, such as a river with crocodiles and poachers' traps. The player is assisted by a dung beetle who presents various geometry challenges, and provides feedback and scaffolding hints.

Figure 4 illustrates selected gameplay screens. Screen A shows a scrollable story with text, images, and background sound. Screens B–C exemplify pedagogical challenges where the player must identify a valid geometric shape. In screen D, the dung beetle congratulates the player and shows rewarded points. Screens E–F illustrate where the player must advance in the story; selecting an island (E) or a stone (F) will take the player to a corresponding pedagogical task. A detailed account of the design process of Leometry and the results of its formative evaluation are presented in [52].

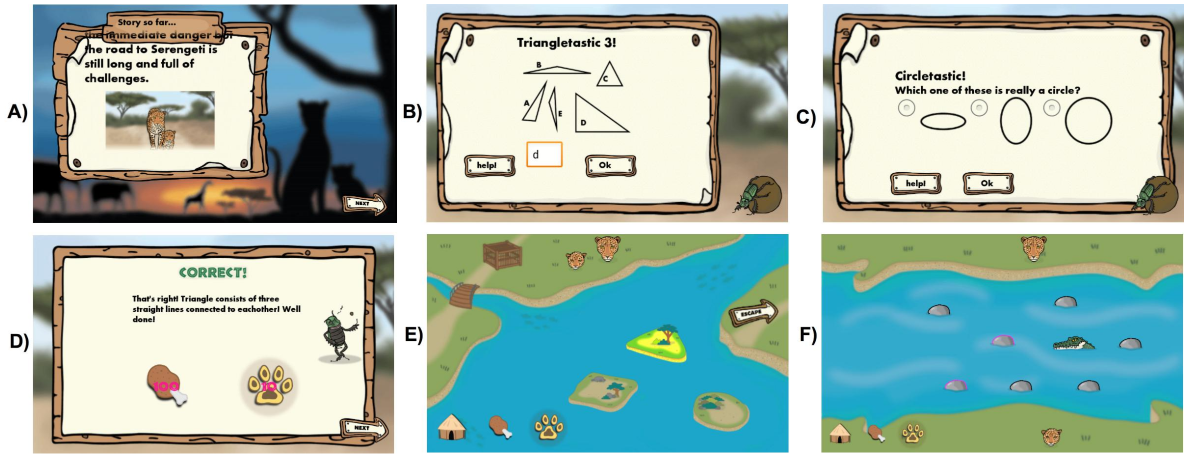

Figure 4. Leometry user interface.

Leometry's pedagogical challenges were prepared jointly with an elementary school teacher and they are based on the Van Hiele model, which describes the process of geometry learning [68]. The game's pedagogical challenges were founded on the first two Van Hiele 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. As with Calory Battle AR, Leometry can be played alone or in a team of two players (Figure 5).

Figure 5. Elementary school students playing Leometry in the Republic of Korea.

The AR features in Leometry were implemented using the game engine developed for Calory Battle AR, thus also having Vuforia SDK as the underlying AR technology. The game uses AR in two ways (see Figure 6): (1) in an AR map of the physical game area (left); and (2) in the boss challenge where the player must search and disarm animal traps set by the poachers (right). The game's story, pedagogical challenges, and animal traps can be distributed around a geographical area, thus requiring the player to move like in Calory Battle AR. The AR map shows virtual hotspots where the story continues or where animal traps are located. To activate a hotspot, the player must touch it with the Multitool. The boss challenge requires the player to find and disarm five poachers' traps. After finding an image target of a trap using the AR map, the player must use the phone's camera to see the virtual trap and touch the pressure plates on the trap in the correct order with the Multitool.

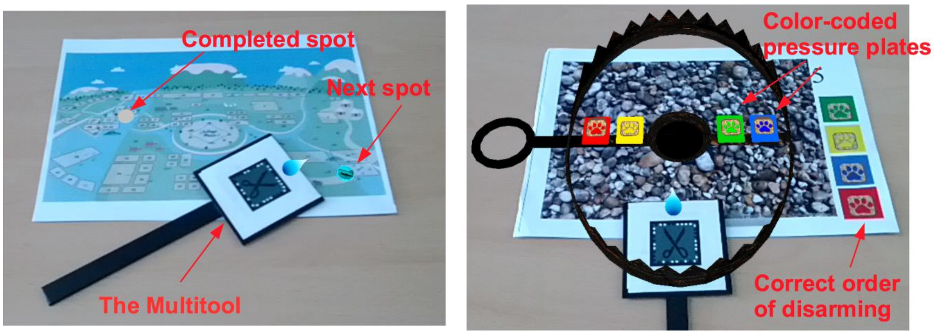

Figure 6. The uses of AR in Leometry.

5. Discussion

The systematic literature review results suggest that EMARGs have been used around the world for various pedagogical purposes in a variety of ways, thus one certainly cannot claim that mobile AR is a one-trick entertainment pony. This observation is aligned with previous reviews conducted on the matter (see Section 2) as well as with the proliferation of AR applications in mobile application stores. Moreover, although mobile AR games with pedagogical goals are lagging far behind Pokémon Go in terms of popularity and appeal, this review shows that the AR technology is mature enough for educators to adopt it for pedagogical purposes. In the following, we shall reflect upon the review results and, informed by the discussion, wrap up the study by giving guidelines for future EMARG development.

5.1. Pedagogy

Several EMARGs focused on learning subjects that require concretization of abstract concepts, such as mathematics and physics. These observations are aligned with previous research results indicating that a key pedagogical affordance of mobile AR is its ability visualize abstract, invisible concepts [4,13]. This works particularly well for children who may not be able to think at similar levels of abstraction as adults. EMARG researchers have also noticed this, which can be seen in the fact that most EMARGs are targeted at elementary school children. Another possible reason for this wide presence of children as target learners is that this study focused on reviewing mobile AR games for education; games are known to possess a variety of motivators that can facilitate learning [69,70], and this is especially so for children. Naturally, concretizing invisible things or abstract concepts with AR is not limited only to educating children; the demonstrative power of AR can also be harnessed in business environments to train employees [71,72] and enhance marketing [73], for example. Similarly, as some of the reviewed EMARGs illustrated, AR-based learning can also be applied to higher education and lifelong learning.

In addition to concretization, there is another important pedagogical affordance of mobile AR that most of the reviewed EMARGs took advantage of: informality. This is closely related to the mobility of the learner due to the use of mobile devices. As the learner becomes mobile, learning can be transferred away from the formal learning setting of a classroom. A direct consequence of this is that learning opportunities multiply as the context surrounding the learner becomes a resource that can be utilized in the learning process. Although a large number of the EMARGs were based on informal contexts, their use of the context as a learning resource was often limited to simple location-awareness, and sometimes even the location was irrelevant. Thus, there is some work to be done in future EMARGs to truly take the advantage of the context as a facilitator of learning. Perhaps we ought to focus on *context-aware AR* instead of mobile AR to emphasize the potential consequences of freeing the user from contextual restrictions.

An important observation from the pedagogical viewpoint is that most of the reviewed EMARGs were not grounded on any learning theory or framework, which may hinder pedagogical effectiveness and even result in negative learning experiences. Finding a suitable learning theory for a given EMARG, or for any learning technology for that matter, depends on the desired learning outcomes and on the context in which the game is to be played. For example, if the EMARG is based on an informal learning context that forms a part of the learning materials, such as a museum with its objects, situated learning [64] could be a suitable learning theory. As another example, if the EMARG is based on a science classroom with the purpose of performing scientific experiments through AR content, problem-based learning theory could make learning processes more effective [74]. Essentially, many learning theories that fall under the umbrella term of constructivist learning are suitable to be used with EMARGs because in constructivism, the learner assumes an active role by constructing new knowledge through the interplay of previous knowledge and current experiences [75]. Moreover, constructivism, as opposed to behaviorism where knowledge is merely transmitted, puts the learner in the center of the learning process, thus granting them a degree of autonomy that traditional lecture-based education rarely affords.

5.2. Augmented Reality

One of the interesting findings of this study is that different definitions of mobile AR exist. When I conducted a literature search for this review, I discovered a rather large number of educational mobile games that claimed to utilize AR. However, a closer inspection revealed that many of these games did not fit to my definition of mobile AR, which explicitly requires that the system must augment the real-world view of a mobile device's camera with virtual content, such as 3D models, graphics, annotations, and animations. The method of target tracking is irrelevant, as long as virtual content appears on top of the camera feed. Several discovered games that claimed to use AR were traditional treasure hunts with location-sensitive learning content displayed on a mobile device, with no indication of camera-based AR materials being provided. These games were typically created with platforms such as ARIS, ARLearn, and FreshAiR, which can be used by non-technical persons to create applications where location-based content is delivered to the user's mobile device. Although their names suggest the use of AR, these platforms do not support AR as per my definition, with the exception of the latest version of ARIS in which a marker-based AR feature is implemented. My conclusion is therefore that there exist multiple definitions and understandings of what mobile AR is, which calls for an agreement on how the term "mobile AR" should be defined and used. The definition should be non-technical so that it can also be understood by educators who may lack the technical foundations required to understand what mobile AR encompasses.

As the mobile AR platform comparison in Table 7 revealed, there are many AR target tracking technologies for developers to choose from. Marker-based tracking (fiducial or image) is an easy, cheap, and widely available solution suitable for most use-cases. However, it may not always work well in outdoor environments (e.g., weather, illumination, vandalism) or in sensitive contexts (e.g., a museum that wishes to keep the environment authentic), and it does require some maintenance effort after initial setup. Alternatively, object-based, location-based, or sensor-based tracking, albeit less supported by AR platforms than marker-based tracking, could be more unobtrusive with a lower likelihood of environmental disruptions and easier maintenance. In particular, object tracking is probably something that we can see increasingly in the future, as machine vision algorithms improve accuracies with the help of deep learning. Other tracking technologies, such as point cloud tracking and face tracking, were marginal and recommendable only for special scenarios.

Whilst there exist many platforms on which mobile AR applications can be created (Table 7) the reviewed EMARGs, or at least those that provided information of the underlying AR platform, were based on a handful of them. One reason for this may be that educational game developers/researchers have limited time and money resources, and thus they may choose a platform which is freely available and has abundance of examples available. Therefore, the popularity of Vuforia SDK does not come as a surprise, given that it has been available for a relatively long time for free, albeit with limitations. Moreover, it has a wide range of features, supports multiple platforms, has good developer support in terms of official and non-official online tutorials, and integrates well into the Unity 3D game engine. Open source AR platforms, such as ARToolKit and its derivatives, were also fairly popular, and these are particularly suitable for developers who prefer to be free from license restrictions of commercial platforms, or who wish to tweak the AR platform to suit their specific needs. However, Vuforia, ARToolKit and other SDK-based AR platforms may not be appropriate for teachers and other non-technical users. For these users, ARIS, Aurasma, and Blippar could be viable choices as they are freely available for educational use and provide content editors that do not require programming skills.

The analysis results suggested that interaction with AR content was mostly based on visualizing virtual content and using the touch screen of a mobile device to interact with the content. This is the most obvious way given that this review focused on mobile devices. Although there were a few EMARGs that used sensor-based interaction [37,43] or interaction through marker manipulation [6,39,52], my impression is that there remains much to be improved in diversifying AR interaction and making it more natural. As a starting point, one can refer to Ducher's [76] review on interaction methods in AR with a specific focus on natural interaction. For example, this review suggests interaction through haptic user interfaces, gesture recognition, gaze-tracking, and speech recognition. Yet it is not a trivial task to design well-functioning natural user interfaces for AR interaction. It would therefore be of tremendous help if developers of AR platforms would integrate a variety of interaction modalities into their products, thus enabling mobile AR game developers to easily mix and match rich sets of AR content and interaction methods. In the same spirit, EMARG developers should offer several media modalities (e.g., 3D, 2D, annotations, animations, sound) through which AR content are presented to the user, thus diversifying the AR experience.

5.3. Gaming

If one were to define a game that best represents contemporary EMARGs, it would probably be a treasure hunt with characteristics of puzzle and adventure genres. The popularity of the treasure hunt genre correlates with the use of mobile devices as clients, which enables deployment of learning content over a geographical area. Moreover, finding hidden "treasures", as well as embarking on a story-driven adventure, promote curiosity, which is known to be a powerful intrinsic motivator [69] and which was very successfully harnessed in Pokémon Go. Puzzle-based EMARGs were also common, which may indicate that the developers of these games did not spend much resources on designing their game concepts. After all, puzzles have typically simple game mechanics, which directly translate to difficulty of implementation. This is not to say that puzzle games do not work; they can be very engaging if done well. Although simplicity is often a desired outcome among designers, sticking to one or two genres can do a disservice to a central goal of educational games: keeping the player engaged in learning for a sufficiently long time. An overly simple game may not be able to catch the player's interest in long-term, thus it may lose its effect as an engaging method for learning. I therefore propose that EMARG developers should carefully consider which game genres would be suitable for their target context and design the game so that it would support not one, but at least two or more game genres, thus diversifying the gameplay experience. This also links to AR interaction modalities discussed above. For example, gesture-based interaction is a good match with the action genre, as Electric Agents illustrated [43].

I chose the Game Bricks model [66] to analyze the gameplay elements of the reviewed EMARGs because the model is compact and yet sufficiently descriptive. Match, Select and Move were the most commonly used game elements. This result directly relates to the game genres discussed above: treasure hunt requires move and match, and puzzles are typically based on selections. This result also indicates that most EMARGs provided largely similar gameplay experience. I was particularly surprised that the Create brick was not used much. After all, constructivism suggests that knowledge is constructed by the learner. For example, a learner could create photographs and other "evidence" of the learning experience in order to revisit it at a later time for reflective purposes. This would also increase ownership towards the learning process, which functions as another motivator for engagement. Aligned with my suggestion to support multiple game genres in future EMARGs, I propose that developers consider using the Game Bricks model or another appropriate framework to implement a rich choice of game elements, thus diversifying the overall gameplay experience.

The choice between single-player and multi-player game modes depends on several factors. Is the goal is to promote social interaction? Does the environment restrict interaction between players (e.g., a quiet library versus a noisy park)? What is the availability of client devices? Does the game concept require a specific mode (e.g., a role-play among a group of players)? It is also possible that the game supports both single-player and multi-player modes. For example, the case studies Calory Battle AR and Leometry are recommended for play in small teams, but they are perfectly playable individually as well. When choosing between cooperation and competition, one must carefully think what are the pros and cons of either mode. Generally, research suggests that cooperation is more effective than competition for reaching achievements [77], but in the world of games and playing, players may have preferred play styles that differ in the social dimension [78]. A good compromise could be to equip a cooperative game with competitive game mechanics, such as a leaderboard containing the points of competing teams [6,36].

5.4. Guidelines for EMARG Developers

I have compiled a set of guidelines, emerging from my analysis of the literature and discussion thereof, that can be used by EMARG developers to improve their designs and perhaps avoid some pitfalls. These 13 guidelines are listed in Table 8 with descriptions.

Table 8. Guidelines for future EMARGs.

Guideline	Description
	Pedagogy
Concretize abstractions	Use AR to show concretizations of abstract concepts and allow hands-on experimentation. This is particularly suitable for subjects such as mathematics, physics and chemistry, where abstract concepts can be difficult to demonstrate and manipulate.
Grounded on learning theory	Base the game and its learning content on an appropriate learning theory or a framework, such as situated learning or problem-based learning
Using the context	One of the pedagogical affordances of mobile technology is that we can involve the context (e.g., surrounding objects) as a learning resource and make the player traverse it. Without using the context, the game could as well be implemented on a PC.
	Augmented Reality
Appropriate AR platform	Use a well-established and freely available platform with good support resources. For example, if you are a game programmer, use Vuforia SDK or ARToolkit (or one of its derivatives); if you are an educator, use ARIS, Aurasma, or Blibbar.
Appropriate target tracking method	Choose a target tracking method according to the location and maintenance resources. This naturally affects the choice of the AR platform and vice versa.
Clear concepts	Make sure to define the core concepts unambiguously. For example, what does mobile AR mean to you?
More than a gimmick	Design your game so that the use of AR is not limited to merely showcasing its "coolness" because the novelty effect is bound to wear out. To do this, you need to understand the versatile ways of using AR and adopt those ways that are suitable for your needs.
Multimodal AR interaction	Provide different possibilities for interaction with AR content through methods such as touch screen, marker manipulation, sensor-based gestures, eye tracking, and speech recognition.
Multimodal AR content	Provide AR content through different media modalities, such as 3D models, 2D pictures, videos, animations, annotations, and sounds.
Provision of a content editor	If you are using an AR platform that does not support non-programmatic content management, provide an easy method for non-technical educators to modify and add new game content, and make sure that they will be trained to use the method.
	Gaming
Multi-genre	Combine game genres to make the game more interesting and suitable for a wider range of play preferences.
Skillful design	Get a skilled designer to create AR content and the game appearance in general.
Versatile gameplay	Use a gameplay model (e.g., Game Bricks) to design many different gameplay components (game bricks) into your game to keep the player engaged and motivated.

6. Conclusions

I embarked on this academic journey because previous reviews, albeit being high in number and versatile in foci, did not thoroughly address the specific area of educational games that utilize mobile AR. My goal was to understand contemporary educational mobile AR games, or EMARGs, from the perspectives of technology, pedagogy and gaming, and thereby provide mobile AR game developers as well as educational technologists with a solid foundation on which to make informed decisions about future EMARG development and usage. By conducting this systematic literature review, I answered the research question: "What are the technological, pedagogical and gaming characteristics of contemporary mobile AR games in the context of education?" Moreover, the two case studies helped illustrate these characteristics even further. Through discussion, I then processed my interpretations that emerged from the results, and summarized these interpretations into 13 guidelines that can be useful to EMARG developers. In total, I believe that this study makes an important contribution to the scientific body of knowledge not only regarding EMARGs but also regarding mobile AR in general.

Although this review provided new information from multidisciplinary perspectives, it is by no means a fully comprehensive account on all aspects related to EMARGs. Therefore, there remain several important challenges to be explored in future research. Firstly, although Ducher [76] did a fairly good job in presenting several methods for interaction with AR content, it is necessary to analyze these interaction methods in detail in the contexts of AR-based games and education, and formulate guidelines for designers to follow. Secondly, this review did not perform a deep analysis of the game mechanics used in EMARGs. Understanding what game mechanics are suitable for mobile AR-based games and how to use these game mechanics is essential for ensuring an engaging gameplay experience. Thirdly, for the sake of learning effectiveness, it is important to ensure that future EMARGs are grounded on a suitable learning theory. To this end, we need research to understand what learning theories can be used with mobile AR games and how they are best applied. Finally, we must start looking beyond AR. Microsoft's Windows Mixed Reality platform (https://www.microsoft.com/en-us/windows/windows-mixed-reality) that combines VR and AR (although not yet mobile) shows a direction where mobile AR could one day lead. Essentially, mixed reality allows deeper immersion in a virtual world whilst involving the physical environment around the user. It would be therefore an interesting research topic to explore what mixed reality could offer in terms of pedagogy, technology and gaming for future learners.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Table A1 presents links to the AR platforms that were analyzed in Section 4.1.5.

Table A1. Links to AR platforms, accessed on 31 January 2018 (see Table 7)

Name	Link
ALVAR	http://virtual.vtt.fi/virtual/proj2/multimedia/alvar/index.html
ANDAR	https://github.com/openube/andar
ARCore	https://developers.google.com/ar
ARIS	https://arisgames.org
ARKit	https://developer.apple.com/arkit
ARToolkit	http://www.artoolkit.org
Augment	http://www.augment.com
Aurasma	https://www.aurasma.com
Blibbar	https://blippar.com
CraftAR	https://catchoom.com/product/craftar
DroidAR	https://bitstars.github.io/droidar
EasyAR	https://www.easyar.com
EON reality	https://www.eonreality.com
Hoppala Augmentation	http://www.hoppala-agency.com
Infinity AR	http://www.infinityar.com
Kudan AR SDK	https://www.kudan.eu
Layar	https://www.layar.com
Maxst AR SDK	http://maxst.com
NyARToolkit	http://nyatla.jp/nyartoolkit/wp/?page_id=198
Rajawali	https://github.com/Rajawali/RajawaliVuforia
Rox AR SDK	http://robocortex.com
ViewAR	http://viewar.com
Void AR	https://www.voidar.net
Vuforia AR SDK	https://developer.vuforia.com/downloads/sdk
Wikitude	https://www.wikitude.com
Xzimg	https://www.xzimg.com

References

1. Baum, L.F. *The Master Key: An Electrical Fairy Tale, Founded Upon the Mysteries of Electricity and the Optimism of Its Devotees*; Bowen-Merrill Co.: Indianapolis, IN, USA, 1901.
2. Sutherland, I.E. A head-mounted three dimensional display. In *Proceedings of the 9–11 December 1968, Fall Joint Computer Conference, Part I on—AFIPS'68 (Fall, Part I)*; ACM Press: New York, NY, USA, 1968; pp. 757–764.
3. Keckes, A.L.; Tomicic, I. Augmented reality in tourism—Research and applications overview. *Interdiscip. Descr. Complex Syst.* **2017**, *15*, 157–167.
4. Wu, H.K.; Lee, S.W.Y.; Chang, H.Y.; Liang, J.C. Current status, opportunities and challenges of augmented reality in education. *Comput. Educ.* **2013**, *62*, 41–49.
5. Lee, B.K. Augmented Reality in Education and Training. *TechTrends* **2012**, *56*, 13–21.
6. Laine, T.H.; Suk, H.J. Designing Mobile Augmented Reality Exergames. *Games Cult.* **2016**, *11*, 548–580.

7. Mao, C.C.; Sun, C.C.; Chen, C.H. Evaluate Learner's Acceptance of Augmented Reality Based Military Decision Making Process Training System. In Proceedings of the 2017 5th International Conference on Information and Education Technology, Tokyo, Japan, 10–12 January 2017; pp. 73–77.
8. Ternier, S.; Klemke, R.; Kalz, M.; van Ulzen, P.; Specht, M. ARLearn: Augmented reality meets augmented virtuality. *J. Univ. Comput. Sci.* **2012**, *18*, doi:10.3217/jucs-018-15-2143.
9. Bacca, J.; Baldiris, S.; Fabregat, R.; Graf, S.; Kinshuk. Augmented Reality Trends in Education: A Systematic Review of Research and Applications. *Educ. Technol. Soc.* **2014**, *17*, 133–149.
10. Radu, I. Augmented reality in education: A meta-review and cross-media analysis. *Personal Ubiquit. Comput.* **2014**, *18*, 1533–1543.
11. Dunleavy, M.; Dede, C. Augmented Reality Teaching and Learning. In *Handbook of Research on Educational Communications and Technology*; Spector, J., Merrill, M., Elen, J., Bishop, M., Eds.; Springer: New York, NY, USA, 2014; pp. 735–745.
12. Cheng, K.H.; Tsai, C.C. Affordances of Augmented Reality in Science Learning: Suggestions for Future Research. *J. Sci. Educ. Technol.* **2013**, *22*, 449–462.
13. Nielsen, B.L.; Brandt, H.; Swensen, H. Augmented Reality in science education—Affordances for student learning. *Nordic Stud. Sci. Educ.* **2016**, *12*, 157–174.
14. Fotaris, P.; Pellas, N.; Kazanidis, I.; Smith, P. A systematic review of Augmented Reality game-based applications in primary education. In Proceedings of the 11th European Conference on Game Based Learning, Graz, Austria, 5–6 October 2017; pp. 181–191.
15. Ferdinand, P.; Müller, S; Ritschel, T.; Wechselberger, U. The Eduventure—A New Approach of Digital Game Based Learning Combining Virtual and Mobile Augmented Reality Game Episodes. In Proceedings of the Game based Learning, Beitrage des Preconference Workshop der 3. Deutschen E-Learning Fachtagung Informatik, Rostock, Germany, 13 September 2005; Fraunhofer IRB Verlag; pp. 79–90.
16. Broll, W.; Lindt, I.; Herbst, I.; Ohlenburg, J.; Braun, A.K.; Wetzel, R. Toward Next-Gen Mobile AR Games. *Mobile Graphics* **2008**, *28*, doi:10.1109/MCG.2008.85.
17. FitzGerald, E.; Ferguson, R.; Adams, A.; Gaved, M.; Mor, Y.; Thomas, R. Augmented reality and mobile learning: The state of the art. *Int. J. Mobile Blend. Learn.* **2013**, *5*, 43–58.
18. Specht, M.; Ternier, S.; Greller, W. Dimensions of Mobile Augmented Reality for Learning: A First Inventory. *J. Res. Center Educ. Technol.* **2011**, *7*, 117–127.
19. Schmitz, B.; Klemke, R.; Specht, M. An Analysis of the Educational Potential of Augmented Reality Games for Learning. In Proceedings of the 11th World Conference on Mobile and Contextual Learning, Helsinki, Finland, 15 October 2012; pp. 140–147.
20. Koutromanos, G.; Sofos, A.; Avraamidou, L. The use of augmented reality games in education: A review of the literature. *Educ. Media Int.* **2015**, *52*, 253–271.
21. Godwin-jones, R. Augmented Reality and Language Learning: From Annotated Vocabulary to Place-Based Mobile Games. *Lang. Learn. Technol.* **2016**, *20*, 9–19.
22. Tobar-Muñoz, H. Supporting Technology for Augmented Reality Game-Based Learning. Doctoral Dissertation, University of Girona, Girona, Spain, 2017.
23. Bressler, D.M.; Bodzin, A.M. A mixed methods assessment of students' flow experiences during a mobile augmented reality science game. *J. Comput. Assist. Learn.* **2013**, *29*, 505–517.
24. Crandall, P.G.; Engler, R.K.; Beck, D.E.; Killian, S.A.; O'Bryan, C.A.; Jarvis, N.; Clausen, E. Development of an augmented reality game to teach abstract concepts in food chemistry. *J. Food Sci. Educ.* **2015**, *14*, 18–23.
25. Gonsalves, A.; Ternier, S.; de Vries, F.; Specht, M. Serious games at the UNHCR with ARLearn, a toolkit for mobile and virtual reality applications. In Proceedings of the 11th World Conference on Mobile and Contextual Learning, Helsinki, Finland, 15 October 2012; pp. 244–247.
26. Klemke, R.; Ternier, S.; Kalz, M.; Schmitz, B.; Specht, M. Immersive multi-user decision training games with ARLearn. In Proceedings of the European Conference on Technology Enhanced Learning, Graz, Austria, 16–19 September 2014; pp. 207–220.
27. Manning, A.; Powers, R.; Pedisich, X. Better Learning Though Augmented Reality: AR in the Classroom. *Anthós* **2012**, *4*, 1.
28. Martin, J.; Dikkers, S.; Squire, K.; Gagnon, D. Learning Through Local Games. *TechTrends* **2014**, *58*, 35–41.
29. Perry, B. Gamifying French Language Learning: A Case Study Examining a Quest-based, Augmented Reality Mobile Learning-tool. *Procedia Soc. Behav. Sci.* **2015**, *174*, 2308–2315.

30. Schmitz, B.; Klemke, R.; Walhout, J.; Specht, M. Attuning a mobile simulation game for school children using a design-based research approach. *Comput. Educ.* **2015**, *81*, 35–48.
31. Shea, A.M. Student Perceptions of a Mobile Augmented Reality Game and Willingness to Communicate in Japanese. Doctoral Dissertation, Pepperdine University, Malibu, CA, USA, 2014.
32. Kamarainen, A.; Metcalf, S.; Grotzer, T.; Browne, A.; Mazzuca, D.; Tutwiler, M.; Dede, C. EcoMOBILE: Integrating augmented reality and probeware with environmental education field trips. *Comput. Educ.* **2013**, *68*, 545–556.
33. Holden, C. ARIS: Augmented Reality for Interactive Storytelling. In *Mobile Media Learning*; ETC Press: Pittsburgh, PA, USA, 2014; pp. 68–83.
34. Hodhod, R.; Fleenor, .S; Nabi, S. Adaptive Augmented Reality Serious Game to Foster Problem Solving Skills. In Proceedings of the Workshop on Hyperrealistic Intelligent Environments, Shanghai, China, 30 June 2014, IOS Press
35. Tobar-Muñoz, H.; Baldiris, S.; Fabregat, R. Augmented Reality Game-Based Learning: Enriching Students' Experience during Reading Comprehension Activities. *J. Educ. Comput. Res.* **2017**, *55*, 901–936.
36. Bühling, R.; Obaid, M.; Hammer, S.; André, E. Mobile augmented reality and adaptive art: A game-based motivation for energy saving. In Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia—MUM'12, Essen, Germany, 10–13 December 2012; p. 1–2.
37. Oppermann, L.; Blum, L.; Shekow, M. Playing on AREEF—Evaluation of an Underwater Augmented Reality Game for Kids. In Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services, Florence, Italy, 6–9 September 2016; pp. 330–340.
38. Young, J.C.; Kristanda, M.B.; Hansun, S. ARmatika: 3D game for arithmetic learning with Augmented Reality technology. In Proceedings of the International Conference on Informatics and Computing, Mataram, Indonesia, 28–29 October 2016.
39. Chatzidimitris, T.; Kavakli, E.; Economou, M.; Gavalas, D. Mobile Augmented Reality edutainment applications for cultural institutions. In Proceedings of the IISA 2013—4th International Conference on Information, Intelligence, Systems and Applications, Piraeus, Greece, 10–12 July 2013; pp. 270–274.
40. Nilsson, S.; Arvola, M.; Szczepanski, A.; Bång, M. Exploring place and direction: Mobile augmented reality in the Astrid Lindgren lanscape. In Proceedings of the 24th Australian Computer-Human Interaction Conference, Melbourne, VIC, Australia, 26–30 November 2012; pp. 411–419.
41. Phipps, L.; Alvarez, V.; de Freitas, S.; Wong, K.; Baker, M.; Pettit, J. Conserv-AR: A Virtual and Augmented Reality Mobile Game to Enhance Students' Awareness of Wildlife Conservation in Western Australia. In Proceedings of the 15th World Conference on Mobile and Contextual Learning, Sydney, Australia, 24–26 October 2016; pp. 214–217.
42. Pombo, L.; Morais Marques, M.; Carlos, V.; Guerra, C.; Lucas, M.; João Loureiro, M. Augmented Reality and Mobile Learning in a Smart Urban Park: Pupils' Perceptions of the EduPARK Game. In Proceedings of the International Conference on Smart Learning Ecosystems and Regional Development, Aveiro, Portugal, 12–13 June 2017; pp. 90–100.
43. Revelle, G.; Reardon, E.; Cook, K.; Takeuchi, L.; Ballagas, R.; Mori, K.; Horii, H.; Raffle, H.; Sandberg, M.; Spasojevic, M. Electric Agents: Combining Collaborative Mobile Augmented Reality and Web-Based Video to Reinvent Interactive Television. *ACM Comput. Entertainm.* **2014**, *12*, 1–21.
44. Eleftheria, C.A.; Charikleia, P.; Iason, C.G.; Athanasios, T.; Dimitrios, T. An innovative augmented reality educational platform using Gamification to enhance lifelong learning and cultural education. In Proceedings of the 4th International Conference on Information, Intelligence, Systems and Applications, Piraeus, Greece, 10–12 July 2013; pp. 258–263.
45. Furió, D.; González-Gancedo, S.; Juan, M.C.; Seguí, I.; Costa, M. The effects of the size and weight of a mobile device on an educational game. *Comput. Educ.* **2013**, *64*, 24–41.
46. Furió, D.; González-Gancedo, S.; Juan, M.C.; Seguí, I.; Rando, N. Evaluation of learning outcomes using an educational iPhone game vs. traditional game. *Comput. Educ.* **2013**, *64*, 1–23.
47. Hsu, T.C. Learning English with Augmented Reality: Do learning styles matter? *Comput. Educ.* **2017**, *106*, 137–149.
48. Lu, Y.; Chao, J.T.; Parker, K.R. HUNT: Scavenger hunt with augmented reality. *Interdiscip. J. Inf. Knowl. Manag.* **2015**, *10*, 21–35.

49. Hwang, G.J.; Wu, P.H.; Chen, C.C.; Tu, N.T. Effects of an augmented reality-based educational game on students' learning achievements and attitudes in real-world observations. *Interact. Learn. Environ.* **2016**, *24*, 1895–1906.
50. Vidal, E.C.E.; Ty, J.F.; Caluya, N.R.; Rodrigo, M.M.T. MAGIS: Mobile Augmented-Reality Games for Instructional Support. In Proceedings of the 3rd Asia-Europe Symposium on Simulation & Serious Gaming, Zhuhai, China, 3–4 December 2016; pp. 191–194.
51. Lan, T.S. Learning through augmented reality mobile game application. In Proceedings of the IEEE Annual Conference International Council for Education Media, Singapore, 1–4 October 2013; pp. 1–5.
52. Laine, T.H.; Nygren, E.; Dirin, A.; Suk, H.J. Science Spots AR: A platform for science learning games with augmented reality. *Educ. Technol. Res. Dev.* **2016**, *64*, pp. 507–531.
53. Lin, C.Y.; Chai, H.C.; Wang, J.Y.; Chen, C.J.; Liu, Y.H.; Chen, C.W.; Lin, C.W.; Huang, Y.M. Augmented reality in educational activities for children with disabilities. *Displays* **2016**, *42*, 51–54.
54. Viinikkala, L.; Heimo, O.I.; Korkalainen, T.; Mäkilä, T.; Helle, S.; Pönni, V.; Arimaa, J.P.; Saukko, F.; Pääkylä, J.; Jokela, S.; et al. The Luostarinmäki Adventure—An Augmented Reality Game in an Open-air Museum. In Proceedings of the NODEM 2014 Conference, Warsaw, Poland, 1–3 December 2014.
55. Martínez Zarzuela, M.; Díaz Pernas, F.J.; Barroso Martínez, L.; González Ortega, D.; Antón Rodríguez, M. Mobile serious game using augmented reality for supporting children's learning about animals. *Procedia Comput. Sci.* **2013**, *25*, 375–381.
56. Alakärppä, I.; Jaakkola, E.; Väyrynen, J.; Häkkilä, J. Using Nature Elements in Mobile AR for Education with. In Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services, Vienna, Austria, 4–7 September 2017.
57. Barma, S.; Daniel, S.; Bacon, N.; Gingras, M.A.; Fortin, M. Observation and analysis of a classroom teaching and learning practice based on augmented reality and serious games on mobile platforms. *Int. J. Ser. Games* **2015**, *2*, doi:10.17083/ijsg.v2i2.66.
58. Eishita, F.Z.; Stanley, K.G.; Mandryk, R. Iterative design of an augmented reality game and level-editing tool for use in the classroom. In Proceedings of the IEEE Games Media Entertainment (GEM), Toronto, ON, Canada, 22–24 October 2014; pp. 1–4.
59. Blanco-Fernández, Y.; López-Nores, M.; Pazos-Arias, J.J.; Gil-Solla, A.; Ramos-Cabrer, M.; García-Duque, J. REENACT: A step forward in immersive learning about human history by augmented reality, role playing and social networking. *Expert Syst. Appl.* **2014**, *41*, 4811–4828.
60. Fitz-Walter, Z.; Tjondronegoro, D.; Koh, D.; Zrobok, M. Mystery at the library: Encouraging Library Exploration using a Pervasive Mobile Game. In Proceedings of the 24th Australian Computer-Human Interaction Conference, Melbourne, VIC, Australia, 26–30 November 2012; pp. 142–145.
61. Boletsis, C.; McCallum, S. The table mystery: An augmented reality collaborative game for chemistry education. In Proceedings of the International Conference on Serious Games Development and Applications, Trondheim, Norway, 25–27 September 2013; pp. 86–95.
62. Santoso, M.; Yan, W.F.; Gook, L.B. Development of Edutainment Content for Elementary School Using Mobile Augmented Reality. In Proceedings of the 2012 4th International Conference on Computer Research and Development, Chengdu, China, 5 May 2012; p. 14.
63. Rogers, K.; Frommel, J.; Breier, L.; Celik, S.; Kramer, H.; Kreidel, S.; Brich, J.; Riemer, V.; Schrader, C. Mobile Augmented Reality as an Orientation Aid: A Scavenger Hunt Prototype. In Proceedings of the 2015 International Conference on Intelligent Environments, Prague, Czech Republic, 15–17 July 2015 ; pp. 172–175.
64. Lave, J.; Wenger, E. *Situated Learning: Legitimate Peripheral Participation*; Cambridge University Press: Cambridge, UK, 1991.
65. Flagg, B. *Formative Evaluation for Educational Technologies*; Routledge: New York, NY, USA, 1990.
66. Djaouti, D.; Alvarez, J.; Jessel, J.P.; Methel, G.; Molinier, P. A Gameplay Definition through Videogame Classification. *Int. J. Comput. Games Technol.* **2008**, *2008*, 1–7.
67. Fogg, B. *Persuasive Technology: Using Computers to Change What We Think and Do*; Morgan Kaufmann: San Francisco, CA, USA, 2002.
68. Van Hiele, P. *English Translation of Selected Writings of Dina van Hiele-Geldof and Pierre M. van Hiele*; Brooklyn College: Brooklyn, NY, USA, 1984; pp. 243–252.
69. Malone, T.W. Toward a theory of intrinsically motivating instruction. *Cogn. Sci.* **1981**, *5*, 333–369.

70. Garris, R.; Ahlers, R.; Driskell, J.E. Games, motivation, and learning: A research and practice model. *Simul. Gam.* **2002**, *33*, 441–467.
71. Le, Q.T.; Pedro, A.; Lim, C.R.; Park, H.T.; Park, C.S.; Kim, H.K. A Framework for Using Mobile Based Virtual Reality and Augmented Reality for Experiential Construction Safety Education. *Int. J. Eng. Educ.* **2015**, *31*, 713–725.
72. Gavish, N.; Gutiérrez, T.; Webel, S.; Rodríguez, J.; Peveri, M.; Bockholt, U.; Tecchia, F. Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. *Interact. Learn. Environ.* **2015**, *23*, 778–798.
73. Bulearca, M.; Tamarjan, D. Augmented Reality: A Sustainable Marketing Tool? *Glob. Bus. Manag. Res.* **2010**, *2*, 237–252.
74. Savery, J.R.; Duffy, T.M. Problem based learning: An instructional model and its constructivist framework. *Educ. Technol.* **1995**, *35*, 31–38.
75. Steffe, L.; Gale, J.E. *The Construction of Reality in the Child*; Lawrence Erlbaum Associates: Mahwah, NJ, USA, 1995.
76. Ducher, P. Interaction with Augmented Reality. *Adv. Embedd. Interact. Syst.* **2014**, *2*, 23–29.
77. Johnson, D.W.; Maruyama, G.; Johnson, R.; Nelson, D.; Skon, L. Effects of cooperative, competitive, and individualistic goal structures on achievement: A meta-analysis. *Psychol. Bull.* **1981**, *89*, 47–62.
78. Bartle, R. Hearts, Clubs, Diamonds and Spades: Players who suit MUDs. *J. MUD Res.* **1996**, *1*, 19.