Journal of Science Education and Technology (2018) 27:433–447
https://doi.org/10.1007/s10956-018-9734-4

Applications of Augmented Reality in Informal Science Learning Sites: a Review

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Abstract

The importance of increasing interest in the STEM disciplines has been noted in a number of recent national reports. While many previous studies have focused on such efforts inside of the formal classroom, comparatively few have looked closely at informal learning environments. We investigate the innovative use of technology in informal learning by reviewing research on the incorporation of augmented reality (AR) at exhibit-based informal science education (ISE) settings in the literature. We report on the common STEM-focused topics that are covered by current AR applications for ISE learning, as well as the different devices used to support these applications. Additionally, we report on the prevalence of positive learning outcomes and engagement factors commonly associated with the use AR applications in informal environments. This review aims to foster continued development and implementation of AR technology in exhibit-based ISE settings by informing the community of recent findings and promoting additional rigorous research for the future.

Keywords Augmented reality · Informal learning sites · AR review · STEM learning

Introduction

The release of the popular "Pokémon Go" game in the summer of 2016 was met with momentous fanfare. The drive to "Catch 'em All" prompted over 750 million downloads of the mobile app and promoted engagement between users in previously unseen ways. This popularity was not taken lightly in the academic world and was the focus of research ranging from a possible treatment for social disorders (Tateno et al. 2016) to the promotion of physical activity (Barkley et al. 2017). This boom was, for most, the first wide-scale introduction to the world of mobile augmented reality (AR) and, while it could mark a change in the mobile gaming industry, it has also opened the eyes of many interested in using such technology for learning.

Recent national calls to action have specified the need to increase interest and engagement in the STEM (science, technology, engineering, and mathematics) disciplines in order to meet the need for STEM graduates in the workforce of the future (Olson and Riordan 2012; Brewer and Smith 2011). While much of this focus has centered on the physical classroom, reports have suggested that informal learning environments can play an essential role in promoting STEM interest as well (Jensen and Lister 2016; Tofield et al. 2003). Falk et al. (2014) defines informal science education as diverse and being housed within a large variety of entities such as science centers, after-school programs, and makers' spaces. While each of these environments has merit, we focus this study mainly on exhibit-based informal science education (ISE) settings such as museums, science centers, and aquariums. This focus comes from the specific call from the National Research Council (2009) to create informal settings that encourage visitor interaction and collaboration. While early reports have suggested museums and other such exhibit-based settings as a key contributor to informal learning, i.e., Rennie et al. (2003) and Falk et al. (1986), there is a need for an updated review as new advances in technology can be used to further enhance educational outcomes in such environments.

Reports have suggested that collaborative gaming may promote social interaction between participants and foster in-

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game learning (Tateno et al. 2016; Sung and Hwang 2013; Nardi and Harris 2006). The unification of these benefits and interactive learning in an informal environment could provide a promising mechanism for encouraging visitor engagement and concept interest. With the technological advances of smartphones and tablets and the more widespread acceptance of head-mounted devices, this union of cutting-edge technology and learning has become much more attainable. Recognizing this, reports have suggested the ability of AR to encourage visitor collaboration in an informal setting while simultaneously giving users a glimpse into the unseen world surrounding many scientific phenomena (Klopfer and Squire 2008; Squire and Klopfer 2007; Dunleavy et al. 2009). Here we focus on the use of AR in a review of studies that investigate its role in promoting content knowledge, engagement, and interest in exhibit-based informal learning environments. While this technology is currently being used for a number of topics, such as history and art, we focus solely on its role in STEM learning due to both an overwhelming need for promoting interest in these disciplines as well as its usefulness in providing insight into the ever-evolving STEM fields.

Definition of Augmented Reality

The first commercial patent for a device designed to deliver an AR experience was issued in 1950 to cinematographer Morton Helig (Matuk 2016). His "sensorama" was designed to create a physically immersive experience for moviegoers that would introduce them to motions, smells, and physical stimulation that would complement images on a screen (Matuk 2016). Since this early introduction, the realm of virtually augmenting the physical world around us has changed drastically. Today, the most widely accepted definition of "augmented reality" comes from Azuma (1997) who argued that AR consists of three important aspects: the combining of virtual and real objects, the ability or opportunity to interact with these objects in real time, and the accurate registration of three-dimensional real and virtual objects. More succinctly, Carmigniani and Furht (2011) refer to AR as a real-time, direct view of a physical environment that has been enhanced by adding virtual computer-generated information. Each of these seems to be based on the "reality-virtuality continuum" proposed by Milgram et al. (1994). This continuum provides a more unifying view of a real environment compared to a virtual environment defined broadly as "mixed reality" (Fig. 1). From this perspective, the world of AR falls closer to a real-world environment than that of a virtual one due to the overlay of virtual settings to what is physically present.

The technology behind the implementation of AR in an educational setting can vary greatly, ranging from the use of a fixed overhead camera and projection screen (Wojciechowski et al. 2003), or a "heads-up display" device that must be worn by the user (Azuma 1997; Hirose 2005), to a more contemporary approach using smartphones, tablets, and personal computers (Pence 2010). Much like other technology-centered endeavors, devices capable of supporting AR have advanced rapidly over recent years. While the use of AR is not limited to one specific device (Broll et al. 2008), the majority of applications today are based on mobile devices such as smartphones and tablets. As such, many of the applications examined here are developed for smart devices that can be downloaded and interacted with in a one-on-one setting.

Modern-day AR is divided into two main categories, image-based (or marker-based) AR and location-based (or marker-less) AR (Cheng and Tsai 2013). Marker-based AR is based on the recognition of physical objects via a device's image capture input and the appropriate placement of virtual content based upon these images (Wojciechowski and Cellary 2013). Typically, this relies on the recognition of a tag, like a quick response code (QRC), in order to position virtual objects in the proper real-world environment. Marker-less AR, by contrast, requires the aid of a location tracking system, typically GPS or Wi-Fi positioning, in order to place virtual objects that can interact with the physical environment (Koutromanos et al. 2015). While marker-based AR seems to have a more practical application in informal learning environments due to its relatively low cost and ease of integration (El Sayed et al. 2011), the recent advancements in smartphone and tablet technology have also led to a boom in the use of marker-less programming for AR applications (Matuk 2016). One example of a marker-based AR that has recently been developed for the Burke Museum of Natural History in Seattle, Washington, is the "Pocket Bats" program from the University of Washington (Santana 2017). This program uses free-to-use AR developmental software to share the results of a local animal morphology research project with the general public via an exhibit-based museum. While this exhibit has yet to be formally evaluated, it provides a glimpse into the future of AR in informal settings.

The 2010 Horizon Report: Museum Edition from the New Media Consortium recognized AR as one of the six featured technologies and suggested its adoption into mainstream museum education within the next two to three years (Johnson and Witchey 2011). This recent time frame has shown many advancements in hardware technology, as well as an influx of user-friendly programming software to create AR applications. For instance, in the last year, both Apple and Google have released user-friendly application development programs that are specific to their operating systems. Apple's ARKit and Google's ARCore both aim to create an interface that will promote developers to advance the world of AR application. With this, the future of the use of AR in the realm of education is poised to expand, and more specifically for the purposes of this paper, as does its application in exhibit-based ISE settings.

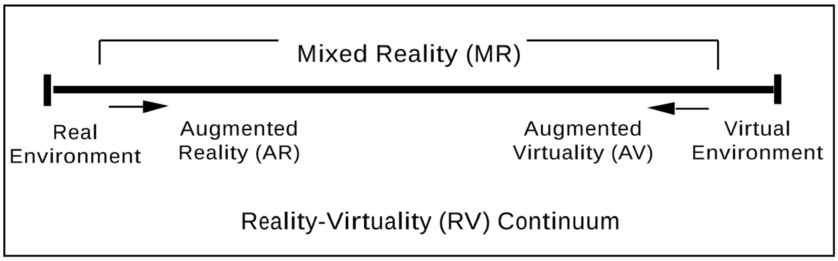

Fig. 1 The reality-virtuality continuum (Milgram et al. 1994)

Applications of Augmented Reality in Education

Recent reports have focused on the use of AR in formal education classrooms. One of these, a literature review by Chen et al. (2017), studied the use AR in formal education between the years of 2011 and 2016. It was noted in this study that of the 55 recent publications, the most commonly reported area of instruction where this technology was used was the sciences (Chen et al. 2017). This prevalence of AR's incorporation in science instruction was also reported in another review focusing on reports between 2000 and 2014 (Koutromanos et al. 2015). One thought behind this preference for science instruction as a topic for AR technology is that the problem-based nature of science lends itself to the investigative and problem-solving strengths of AR design (Koutromanos et al. 2015). In addition to topics of instruction, Chen et al. (2017) also reports that, most prevalently, research focused on the use of smartphones and tablets as a vehicle for AR programming. With the recent technological advances of such devices as well as the lower cost, greater acceptance, and general prevalence of applications that run on these devices, it appears as though this may be the most promising method of AR introduction in the future.

One point that is consistent across reviews on the use of AR in formal education settings is that it most commonly leads to higher academic outcomes when compared to traditional lecture-based instructional techniques (Chen et al. 2017; Koutromanos et al. 2015). Among these outcomes are increases in academic performance ($d = 0.91$; (Chiu et al. 2015), increases in motivation to learn (Di Serio et al. 2013), increases in content engagement (Kamarainen et al. 2013), and increases in content retention ($d = 0.75$; (Vincenzi et al. 2003). By comparison, the reported detriments to learning typically only noted as being a possibility of attention tunneling and difficulty with classroom integration (Radu 2014). It is also of note that the effect size of AR on academic performance ($d = 0.91$) is considerably higher than those with other technology-based instructional strategies such as interactive video ($d = 0.52$) and simulations ($d = 0.33$; (Hattie 2012). As the technology advances and can to be catered to specific educational purposes, it is feasible that the small shortcomings of AR can be rectified in the future.

The previous reports on the use of AR in formal education settings also provide a background for its progression to settings outside of the traditional classroom. Two national reports have called for an increased focus on improving motivation and interest in the STEM disciplines (Olson and Riordan 2012; Brewer and Smith 2011). Exhibit-based ISE settings, such as museums and zoos where individuals can interact on a more personal level with STEM content, seem to be a logical environment to encourage this increase in interest and motivation (Staus and Falk 2017; Habig et al. 2016). With the reported benefits of AR in formal settings (Chen et al. 2017; Koutromanos et al. 2015; Radu 2014), the unification of a rich learning environment with such an effective learning tool could have promising results. While the implementation of AR in informal STEM learning is still in its relative infancy, we report what is currently known in the hopes of fostering continued development and implementation of AR exhibits in ISE settings.

Theoretical Background

Much of the thought behind the outcomes associated with AR can be explained using the "cognitive theory of multimedia learning" proposed by Mayer (2005) as part of the program development process. Sommerauer and Müller (2014) investigates this by arguing that well-designed AR specifically incorporates five specific facets that make up Mayer's cognitive theory of multimedia learning. The first facet, the multimedia principle, notes that learners show greater learning when words are complemented with images during the learning process than when presented alone. Augmented reality can be developed around this theory by virtually supplementing words or images to an existing environment. This could include the addition of virtual text to preexisting physical objects as well as the addition of virtual three-dimensional images onto a preexisting text. The second, spatial contiguity, and third, temporal contiguity, facets work in unison to promote learning by noting that when space and/or time between learning elements is minimized, learning is again enhanced. Augmented reality programs can accommodate this theory by placing appropriate virtual information in coinciding spatial or temporal relation to the physical exhibit or object. The fourth facet noted by Sommerauer and Müller (2014), the modality principle, states that learners benefit more from spoken words than written text when learning with multimedia. Augmented reality can also be developed to account for this by providing learners with audible information throughout the learning experience. In addition, as the technology changes, more AR applications are being designed for mobile devices that can be equipped with headphones that will allow for a more personal listening experience. Lastly, the fifth facet of the cognitive theory of multimedia learning examined by Sommerauer and Müller (2014) was the signaling principle. This principle states that learners show increases in learning when essential information in the learning process is highlighted, or accented, directly during the learning experience (Mayer 2005). Augmented reality can again be developed to accommodate this aspect of multimedia learning theory through the enhancement of specific areas of interest with either virtual imagery or text. These cues could then help guide the learner to what is most important about the topic and could thereby aid in making connections between key points in the lesson.

In addition to development practices founded in multimedia theory, many AR applications have been developed to adhere to both constructivist and situated learning theories (Koutromanos et al. 2015). Constructivist learning theory focuses on encouraging the learner to think and construct their knowledge based on information gained from the world around them (Fosnot and Perry 1996). The application of this theory can logically be incorporated into AR design to encourage learners to explore the environment around them, both real and virtual, and collaborate with their fellow students to form their understanding of the presented topic (Echeverría et al. 2012). Likewise, situated learning theory focuses on the formation of knowledge through social interaction in an active, real, and/or augmented environment. This theoretical framework is also conducive to learning in a setting integrated with AR and has previously been a key focus of development of AR games for education (Squire and Klopfer 2007). Together with the principles of multimedia learning, constructivism and situated learning theory can provide those developing applications for use in both formal and informal learning environments a solid background for the design of future software.

Research Goal of This Review

This review investigates the role of AR in exhibit-based ISE settings (e.g., museums, zoos, and aquariums). In order to accomplish this goal, we more specifically aim to answer the following questions:

1. What specific STEM concepts are commonly the focus of AR applications in informal STEM learning contexts?
2. What are the common design elements of AR applications created for exhibit-based ISE settings?
3. What technological devices are most commonly used to distribute AR applications in exhibit-based ISE settings?
4. What outcomes are commonly reported as a part of studies investigating the use of AR in exhibit-based ISE settings?

Methodology

We gathered primary literature by conducting literature searches using the databases "ScienceDirect," "Google Scholar," "Web of Sciences," and "ERIC: Education Resources Information Center." To encompass as much of the literature as possible, we searched published reports using the specific search phrases of "augmented reality informal," "augmented reality museum," "augmented reality STEM," "augmented reality science," and "augmented reality education." Results were limited to published papers that focused on research conducted in exhibit-based informal learning sites and on topics related to the STEM fields. This included examination of application efficacy as well as investigation into the general use of AR in the informal learning center as a whole. No restrictions were placed upon investigated individuals' age or level of education; however, this information is presented as part of the data if it was provided in the original study. Table 1 outlines the list of studies included in this study and provides details on methods and outcomes for each.

Review Findings

Our investigation into primary research on the use of AR in exhibit-based ISE settings resulted in 17 papers that met the search criteria for this review (Table 1). Out of the 17 published papers, all but one of the papers focused on the investigation of a specific application to explore either specific scientific concepts or a science museum/center as a whole. The one exception to this (Sommerauer and Müller 2014) investigated concepts related to mathematics as they were presented in an exhibit-based informal learning environment. Across all included studies, there were a total of approximately 1463 participants. Of the total, 57% ($n = 834$) of participants of the age of most K-12 students (5–19 years old). The remaining 43% of individuals either ranged in ages from 20 to 79 years of age or were represented in studies that did not report an age range. Participants in this higher age group were only reported in four of the 17 studies presented. The focus on younger participants could speak both to the target audience of the majority of ISE settings and the possible focus on application development targeted for younger individuals.

Table 1 List of papers included in the review

Author(s)	Aims of study	Application description	Design elements of application	STEM concept explored	Sample	Location	Device type	AR system	Measures	Outcomes of study
Hsi (2003)	To examine a device designed to promote visitor interaction with museum content.	Virtual guidebook to promote visitor interaction with exhibits.	Designed to guide visitors through museum and encourage visitor interaction with exhibits	Multiple exhibits based on a variety of science concepts.	$n = 15$ (all ages)	The Exploratorium Science Museum Observational study	Electronic guidebook (PDA) connected to museum Wi-Fi	Image-based (mounted sensors)	Researcher-created qualitative survey and interviews	1.) Users reported that the device motivated them to try new ways to interact with the exhibit. 2.) Device placed user "closer to the concept" which promoted inquiry
Klopfer et al. (2005)	To determine the effectiveness of the "Mystery at the Museum" application for museum exploration.	"Mystery at the Museum": application to promote exploration of an entire science museum and collaboration between visitors.	Designed to: 1.) Engage visitors more deeply in museum exhibits. 2.) Engage visitors more broadly across museum exhibits. 3.) Encourage collaborations between visitors.	Museum-wide science exploration application (not focused on one specific concept)	$n = 40$ (late elementary through middle school-aged children and their parents)	Boston Museum of Science Observational Study	Pocket PC and walkie-talkie	Location-based using museum Wi-Fi	Researcher-created survey to assess participants on interests in the museum, technology, and collaboration.	Positive responses in regard to promoting visitor engagement and collaboration. Promoted comfort with technology.
Sotiriou and Bogner (2008)	To demonstrate an innovative approach that cross-cuts the boundaries between school, museums, research centers, and science theme parks and involves students and teachers in extended playful learning.	The CONNECT platform used to create exhibit on friction.	Designed to promote engagement with the exhibit and collaboration between visitors.	Physical science (friction)	$n = 119$ (ages 15–16 years old)	Science museum Quasi-experimental design	Head-mounted device	Image-based	1.) Intrinsic motivation inventory (Deci and Ryan 1993) 2.) User-created content questions (pre/post-test).	Participation positively influences students' intrinsic motivation and cognitive learning.
Kitalong et al. (2009)	To create a narrative map of the typical visitor interaction with the exhibit.	Journey with sea creatures: AR screen that projects prehistoric sea creatures over an existing dinosaur-centered exhibit.	Designed to create an AR experience to close the gap between formal classroom instruction and informal learning	Cretaceous period sea creatures	Report based on an "archetypal composite user personas created from center visitors" (no *n* reported)	Orlando Science Center Observation study	Projection screen kiosk	Image-based	Visitor interviews	Interview respondents expressed increased interest in learning more about the topic and reported being more engaged and aware of the learning possibilities from user interaction.
Salmi et al. (2009)	To determine the effectiveness of the CONNECT project and EXPLOAR service in exhibit design for informal learning.	The CONNECT platform used to create hot air balloon exhibit.	Designed to involve visitors with extended periods of playful learning by allowing them to feel and interact with exhibits.	Boltzmann constant: temperature and molecular movement	$n = 78$ (ages 11–15 years old)	Heureka Science Center Observational study	Head-mounted device	Image-based	1.) Visual reasoning ability (Raven 2000) 2.) Motivation questionnaire (Deci and Ryan 1993; Salmi 1993) 3.) 13 user-created content questions	1.) High achievers did best on the post-experience knowledge test; however, low achievers showed the most improvement from pre to post. 2.) All achievement groups showed

Table 1 (continued)

Author(s)	Aims of study	Application description	Design elements of application	STEM concept explored	Sample	Location	Device type	AR system	Measures	Outcomes of study
									4.) Prior achievement based on school grades.	positive motivation outcomes.
Asai et al. (2010)	To determine the effectiveness of collaborative learning enabled by integrating tabletop AT and virtual environments.	Scenarios based on quasi-role play where one person (typically a child) assumes the role of an astronaut and another person (typically a parent) acts a mission commander.	Designed to promote collaboration between museum visitors	Lunar exploration	$n = 155$ (ages 8–70 years old)	Modern Industrial Science Museum Observational study	Fixed position computer on a tabletop exhibit	Image-based	1.) A 5-question user-created content quiz. 2.) A 12-question user-created quiz on the participant experience (scored on a 4-point Likert scale)	1.) > 98% correct answers on all content quizzes. 2.) 91% positive responses to questions related to enjoyment. 3.) 85% positive responses on questions related to satisfaction with the interface. 4.) < 70% positive responses to questions related to ease of use.
Snyder and Elinich (2010)	To determine if the AR projection impact student understanding of the science content.	Three fixed position exhibits. Testing only took place in the exhibit focused on electricity.	Designed to satisfy the "7 characteristics of family-friendly exhibits" (Borun and Dritsas 1997)	Electricity, circuits, geology	$n = 8$ (middle school students)	Science Museum Quasi-experimental design	Fixed position computer	Image-based	User-created qualitative surveys	1.) All students in the AR group remained engaged with the exhibit for longer than four minutes. Only one in the control group tyremained engaged past the four-minute mark. 2.) Students in the AR group showed higher levels of experimentation than the control group.
Salmi et al. (2012)	To analyze the use of AR in the Science Center to Go project.	Science Center to Go—portable science center. The device is brought to a school setting in order to set up a "virtual" science center.	Designed to promote knowledge building by following the 5E (inquiry approach) to learning (Bybee 1989)	Thermal motion, wing dynamics, wave-particle duality, Doppler effect, rigid body motion	$n = 292$ (128 in-service teachers, 164 teaching students)	School setting transformed into portable science center Quasi-experimental design	Laptop computer in a fixed position	Image-based	New educational model or paradigms (Salmi 2012)	1.) Instructors found AR to be a better stimulator of the learning process ($p < 0.00$) and provider of feedback ($p < 0.00$) than the control group. 2.) Could be most beneficial if center trips were bracketed with pre/post content. 3.) Instructors found AR to be effective in exhibiting the invisible.

Table 1 (continued)

Author(s)	Aims of study	Application description	Design elements of application	STEM concept explored	Sample	Location	Device type	AR system	Measures	Outcomes of study
										4.) Prices are less of a concern as technology advances.
Yoon et al. (2012)	To help understand how improved conceptual knowledge can be achieved in a museum setting using AR technology.	Be the path—fixed position exhibit on electrical conductivity	Designed to visualize electrical currents in circuitry. Scaffolding within the application itself varied depending on treatment group.	Electrical conductivity	$n = 119$ (middle school students, grades 6–8)	Museum visited as part of a school field trip Quasi-experimental design	Fixed position computer	Image-based	Researcher created content questions and qualitative observation based on measures from Corbin and Strauss (2008).	1.) Students exhibited greater cognitive gains when scaffolds were used along with AR learning. 2.) Only students who were not exposed to AR in the activity did not show significant learning gains.
Takahashi et al. (2013)	To investigate: 1.) the use of AR to attract user interest 2.) the ability of users to interact with the device 3.) the ability of AR to construct knowledge	Laser-based overlay of Baleen whale fossil display	Designed to promote knowledge building and exploration into by providing additional information on the display	Baleen whale fossil	$n = 33$ (ages 5–15 years old)	Museum of Earth, Life and the Sea Quasi-experimental design	"Big Fat Wand" laser projection device	Image-based	Researcher created content questions and opinion surveys.	1.) Based on qualitative interviews, AR encouraged learners to interest in the exhibit. 2.) Based on qualitative interviews, the AR device was easy to use for learners. 3.) No conclusions made in regard to the construction of learners' knowledge due to most participants having high levels of prior knowledge.
Sommerauer and Müller (2014)	To measure the effect of AR on acquiring and retaining mathematical knowledge in an informal learning environment.	A program designed using the "Aurasma" mobile application particularly for this site.	Designed AR application adhering to the "Cognitive Theory of Multimedia Learning" (Moreno and Mayer 1999)	(Mathematics) Cycloids, hyperboloids, linear and exponential growth, historical calculators, approximation of pi, explanation of the Monty Hall equation, attributes of a plane mirror	$n = 101$	"Anonymous" national museum Pre/post crossover field design	Smartphone/ tablet	Location-based	Researcher created content questions.	1.) Significantly higher learning gains from AR group than control ($p < 0.005$) 2.) Based on qualitative interviews, users perceived AR as a valuable add-on of exhibits. 3.) In interviews, users stated they wished to see more AR experiences in museums in the future.
Yoon and Wang (2014)	To explore the affordances of an AR tool on learning focusing on magnets and magnetic fields.	Magnetic Maps—interactive display showing the effects of magnetic fields on magnetism	Designed AR application adhering to the theories of dynamic visualizations in learning.	Magnets and magnetic fields	$n = 70$ (students in grades 5–7)	Museum Quasi-experimental design	Fixed position computer	Image-based	Modified Critical Thinking Skills Checklist from Luke et al. (2007).	1.) Learners interacted significantly longer when using AR compared to control ($p < 0.01$) 2.) Learners show higher levels of

Table 1 (continued)

Author(s)	Aims of study	Application description	Design elements of application	STEM concept explored	Sample	Location	Device type	AR system	Measures	Outcomes of study
										cognitive behaviors compared to control ($p < 0.05$) 3.) Digital augmentation acted as a "scaffold" for users to build knowledge.
Zimmerman et al. (2015)	Examine the talk that results when families are supported to make observations and connections to scientifically relevant concepts	Tree Investigators—interactive application for identification and classification of flora.	Designed AR application to be guided by a naturalist in an arboretum. Designed scaffolding to be part of the learning process within the application.	Flora identification and biodiversity	$n = 25$ (15: 7–11 years old; 10: 18+)	Arboretum Observational design	Smartphone/tablet	Image-based	Video transcribed and analyzed according to recommendations of Derry et al. (2010).	1.) Interaction with AR supported scientific talk and increased knowledge on biodiversity. 2.) Human interaction may act as a "temporary scaffold."
Hsiao et al. (2016)	To: 1.) design a manipulative AR system for instruction on climatology. 2.) discover if different learning instruments make an impact on achievement. 3.) discover if students tend to learn natural science more readily using MAR system.	Weather Observers—manipulative augmented reality application for use in understanding weather.	Designed AR application to allow users to manipulate variables in a way that promotes exploration and knowledge building.	Climatology and weather patterns	$n = 64$ (students in grade 6)	Museum, home, and school Quasi-experimental design	Smartphone/tablet	Image-based	Researcher created content questions and satisfaction questionnaire.	1.) MAR system was effective and produced greater content knowledge outcome than comparison groups ($p < 0.001$) 2.) Manipulative AR allowed users to interact with content and was useful in conveying understanding.
Huang et al. (2016)	Investigate the efficacy of EDALS for learning on ecology in a fixed botanical garden environment.	EDALS—eco-discovery AR-based learning system for plant diversity investigation	Designed AR application based on Kolb's experiential learning theory (Kolb 1981) to provide users a more interactive experience.	Ecology—plant diversity	$n = 21$ (middle school students)	Botanical garden Quasi-experimental design	Smartphone/tablet	Image-based	Activity assessment adapted from Abdullah (2014).	1.) Compared to the control group, EDALSS successfully stimulates positive emotions and improved learning outcomes among learners ($p < 0.05$). 2.) EDALS was reported to be more engaging than control group ($p < 0.05$) 3.) The EDALS group showed significantly higher learning outcomes than the control ($p < 0.05$)

Table 1 (continued)

Author(s)	Aims of study	Application description	Design elements of application	STEM concept explored	Sample	Location	Device type	AR system	Measures	Outcomes of study
Salmi et al. (2016)	To analyze learning using AR technology and the motivational and cognitive aspects related to it in an informal learning context.	AR added to five already existing exhibits on concepts of physical science.	Design was focused on the introduction of AR technology to already existing exhibit in order to enhance understanding of the presented topic	1.) Doppler effect 2.) Boltzmann molecule movement 3.) Young experiment 4.) Aeroplane mini wing exhibit 5.) Rolling double cone	$n = 146$ (11–13 years old)	Science center Quasi-experimental design with pre/posttest	Fixed position computer	Image-based	Deci-Ryan Motivation Scale (Deci and Ryan 2012), SRQ-A Test (Ryan and Connell 1989), Raven Standard Progressive Matrices (Raven 2003), and Researcher created content questions	1.) Increased motivation and interest correlated with increased post-test scores. 2.) Boys and girls both learned equally well in the sample. 3.) AR was most beneficial for the lowest achieving students.
Atwood-Blaine and Huffman (2017)	To study the impact of a mobile AR game on student interactions in a science center.	The Great STEM Caper—center-wide application to promote interaction and collaboration in a science center.	The design was to promote collaboration among users and increase interaction between users and center exhibits.	Science center-wide application. There was no specific focus on one STEM concept	$n = 121$ (students in grades 5–8)	Science center Quasi-experimental design	Smartphone/tablet	Location-based	Researcher created content question and qualitative observations.	1.) An overall increase in user "fun/interest" with use of the mobile game. 2.) Females demonstrated a significant correlation between number of challenges completed and their perception of difficulty while males showed a significant correlation between the number of challenges completed and their enjoyment 3.) Mobile game has a potential to increase visitor engagement and attendance.

Content Focus

While the use of augmented and virtual reality for learning in an informal setting has been incorporated across content areas (Hirose 2005), the nature of STEM learning particularly lends itself to the specific advantages of AR technology (Cheng and Tsai 2013; Chen et al. 2017). Of the studies selected for this review, 47% ($n = 8$) focused on applications that were specific to physical science topics including magnetism, magnetic fields, and flight dynamics (Sotiriou and Bogner 2008; Salmi et al. 2009; Asai et al. 2010; Snyder and Elinich 2010; Salmi et al. 2012; Yoon et al. 2012; Yoon and Wang 2014; Salmi et al. 2016). By comparison, 29% ($n = 5$) of the studies focused on life science topics such as fossils and biodiversity (Kitalong et al. 2009; Takahashi et al. 2013; Zimmerman et al. 2015; Hsiao et al. 2016; Huang et al. 2016). Of note was that all of these life science applications were designed to teach topics that are considered more of a macroscopic view of the natural world, i.e., flora/fauna investigation and biodiversity. While the use of multimedia to supplement cellular and molecular biology topics in a formal classroom is not unusual and has previously been shown to be advantageous to the learning process as compared to traditional instruction ($d = 0.40$; (Goff et al. 2017a), this realm of topics may be underrepresented in informal exhibit-based settings. In addition to physical and life sciences, one of the studies focused on mathematics topics (Sommerauer and Müller 2014) and three focused on a museum-wide application (Atwood-Blaine and Huffman 2017; Hsi 2003; Klopfer et al. 2005).

Design Elements

During the course of this review, it became evident that, while most papers mentioned the theoretical background that was taken into consideration during the development process, there were limited details on the specifics of design and coding. Of the selected studies, 35% ($n = 6$) make mention of learning scaffolds or constructivist knowledge building based on experiences as part of the possible success of their applications (Yoon et al. 2012; Takahashi et al. 2013; Salmi et al. 2012; Zimmerman et al. 2015; Hsiao et al. 2016; Yoon and Wang 2014). In each, both situated learning theory (Lave and Wenger 1991) and Kolb's experiential learning theory (Kolb 1981) were considered throughout the design and development of the AR programs examined. Situated learning focuses on presenting knowledge in an authentic context that requires a community of practice centered on social interaction and collaboration (Lave and Wenger 1991). Similarly, experiential learning theory notes that knowledge is created through the transformation of experience (Kolb 1981). These aspects are theoretically similar and their inclusion as part of development are both proposed strengths of the use of augmented/virtual reality to supplement learning (Bacca et al. 2014; Carmigniani and Furht 2011). The strength of these technologies to allow users to interact with materials in an open learning space during a specified time that is appropriate to internalizing the content presented could, theoretically, aid students in garnering a greater level of understanding. A focus on creating experiences to engage guest and promote collaboration, an aspect of situated learning theory, was also a prominent focus in designing the applications discussed and was specifically mentioned in 65% ($n = 11$) of the studies (Hsi 2003; Klopfer et al. 2005; Sotiriou and Bogner 2008; Kitalong et al. 2009; Salmi et al. 2009; Asai et al. 2010; Snyder and Elinich 2010; Yoon and Wang 2014; Zimmerman et al. 2015; Huang et al. 2016; Salmi et al. 2016). Snyder and Elinich (2010) specifically note the need to promote a family-friendly guest experience by following the "7 characteristics of family-friendly exhibits" (Borun and Dritsas 1997). Game design theory (Klopfer et al. 2005) and Lazzaro (2004) theories on fun (Atwood-Blaine and Huffman 2017) were also a part of the design emphasis of two of the studies explored. One study (Hsi 2003) also implemented the digital guidebook theories of Woodruff et al. (2001)) as part of their design in a museum-wide AR tour application. Two of the studies (Yoon and Wang 2014; Sommerauer and Müller 2014) also specifically note an adherence to design guidelines focusing on multimedia learning theory (Mayer 2005). Several others, while not specifically citing the work, do have aspects of Mayer (2005) theories as part of their multimedia displays (Sotiriou and Bogner 2008; Kitalong et al. 2009; Salmi et al. 2009; Yoon et al. 2012; Yoon and Wang 2014; Hsiao et al. 2016; Huang et al. 2016). Mayer's guidelines for multimedia development and design have previously been shown to promote learning in a formal setting when using multimedia designed for delivering content as compared to traditional instruction ($d = 0.44$; (Goff et al. 2017b). As a result, attention to these and other multimedia guidelines during development of AR for informal settings could also encourage further developmental gains in AR technology. While a unifying theory of design is not necessarily shared across each of the studies presented in this review, each of the theories explored individually has specific merit in the development of each application studied. Future design guidelines should take into account each of the theories collaboratively as practitioners' plan and discuss the development of AR technology for education.

Augmented Reality Devices

The recent advancements in augmented/virtual reality technology have led to a variety of implementation options in informal learning environments (Pence 2010; Bacca et al. 2014). Of the studies in this review, 41% ($n = 7$) used smartphones/tablets as a means of application implementation. Of these seven studies, five were published in the past three years (Sommerauer and Müller 2014; Zimmerman et al.

2015; Hsiao et al. 2016; Huang et al. 2016; Atwood-Blaine and Huffman 2017). In addition, two of the studies (Hsi 2003; Klopfer et al. 2005), both published over ten years ago, used a "pocket PC" or "PDA" device which can be considered a precursor to the modern smartphone/tablet. Fixed position computer systems or head-mounted devices were used as an implementation device in nine of the studies (Salmi et al. 2009; Asai et al. 2010; Sotiriou and Bogner 2008; Kitalong et al. 2009; Yoon et al. 2012; Snyder and Elinich 2010; Salmi et al. 2012; Yoon and Wang 2014; Salmi et al. 2016), but we note that only two of these were published in the last five years (Salmi et al. 2016; Yoon and Wang 2014). The dichotomy of the use of fixed systems versus mobile systems for AR technology speaks to both the usefulness and the cost of new emerging smartphone/tablet applications. While fixed location computer systems or head-mounted devices have been suggested to assure a uniform experience to users (Yoon et al. 2012; Azuma et al. 2001), these may not always be cost-effective for application site-wide (Salmi et al. 2012). The use of mobile apps housed on a user's own smartphone/tablet can provide a much more cost-effective and versatile alternative to fixed systems (Pence 2010). We do note, however, that ownership of a mobile device with data accessibility is not universal. Informal science learning sites should consider this in exhibit development so as to make sure experiences are inclusive as possible, especially given prior research which documents that underrepresented groups, including those from low-income communities, often feel excluded from ISE settings (Dawson 2014). As individuals become better versed in application development and computer coding, it is plausible that future studies will focus more on the use of mobile devices and diverge from more traditional fixed AR devices in informal learning settings. One study implemented AR in a museum exhibit using a proprietary fixed device known as the "Big Fat Wand" or "BFW" (Takahashi et al. 2013). While the outcomes of this study reported its ability to attract learners' interest and to promote learning, this specific device is currently not as widely used as compared to mobile devices and may fit more generally into the category of fixed implementation devices.

Outcomes of Augmented Reality in Informal Science Learning Sites

Of the studies in this review that had a specific focus on academic achievement and understanding, there were significantly higher positive outcomes in both content acquisition and retention with exhibits for individuals using the AR applications being studied when compared to control groups (Sommerauer and Müller 2014, $p < 0.005$; Hsiao et al. 2016, $p < 0.001$; Huang et al. 2016, $p < 0.05$). This again speaks to the possible benefits of AR and technology in an informal learning environment. However, in addition to learning outcomes, of specific interest in all of the studies was the ability of AR technology to increase the level of interest and/or engagement of visitors with the presented concepts (Hsi 2003; Klopfer et al. 2005; Sotiriou and Bogner 2008; Kitalong et al. 2009; Salmi et al. 2009; Asai et al. 2010; Snyder and Elinich 2010; Salmi et al. 2012; Yoon et al. 2012; Takahashi et al. 2013; Yoon and Wang 2014; Zimmerman et al. 2015; Salmi et al. 2016; Atwood-Blaine and Huffman 2017). It can be argued that this could be an even more important outcome of the use of AR in informal learning settings than simply acquiring knowledge. While it is certainly the goal of these learning centers to actually nurture content acquisition, without first promoting interest in STEM topics, this outcome can be limited. One possible important aspect of interest and engagement that has been previously reported on is the promotion of collaboration between individuals. Three of the studies specifically noted that using AR games in an ISE environment stimulated visitors to work together to solve problems and collaborate to reach an ultimate end goal (Yoon and Wang 2014; Kamarainen et al. 2013; Atwood-Blaine and Huffman 2017). Engagement theory notes that collaboration is a key component of active engagement in a learning activity, thus accentuating the usefulness of collaboration in the informal science learning process and its importance in future AR application designs (Kearsley and Shneiderman 1998).

Two of the studies in this review also noted differences in the outcomes of using AR based on the gender of the participants. Salmi et al. (2016) noted in their study on an AR game for use in an ISE setting that while boys scored higher on the initial pre-test assessment ($d = 0.57$), the learning gains after interaction with AR technology were not significantly different between both boys and girls. Additionally, boys in this study exhibited higher motivation and enjoyment, and interested in regard to interaction with AR (path coefficient = 0.84; (Salmi et al. 2016). While overall interest and positive feelings regarding gaming have previously been reported to be higher for males than females (Bonanno and Kommers 2008), there were no significant differences documented in academic learning gains in this study. Atwood-Blaine and Huffman (2017) delved into these differences with slightly more detail noting from participant interviews that females specifically reported enjoying more aspects of the experience that elicited emotion ("hard fun") and participant interaction ("collaborative fun"), while males enjoyed the simple process of playing ("easy fun") and the aspects of real-world competition ("competitive fun") associated with AR applications. Exit interviews also showed that females were found to be more persistent in the face of difficulty compared to their male counterparts (Atwood-Blaine and Huffman 2017). While only noted in a small subsection of the studies, future research should investigate these gender differences further in hopes of maximizing the AR experience in informal settings for everyone. Further, this preliminary evidence suggests that AR technology may be particularly useful in engaging girls' STEM interest. Prior research indicates that attempts to engage girls with STEM materials in ISE by simply changing the color of the materials to stereotypically feminine colors (pastel colors) are ineffective (Mulvey et al. 2017). However, it appears that girls' engagement with this AR technology, although perhaps different than boys, led to higher knowledge gains compared to their boy counterparts (Atwood-Blaine and Huffman 2017). Thus, AR may be an important new platform for encouraging STEM interest and engagement among both boys and girls.

Future Research

The future of AR seems poised for great expansion in the realm of exhibit-based ISE settings. While some museums continue to rely on fixed AR systems, technological advancements point to a wider acceptance of mobile applications that are both more cost-effective and user-friendly (Furió et al. 2013). With the recent adoption of AR technologies in ISE settings nation-wide, future research should focus on the evaluation of these projects that have yet to undergo systematic review. Currently, many of the academic advantages of such technologies are evident; however, future research would also benefit from the investigation into specific developmental protocols for app development that would enhance learning in ISE environments. Our reports show that the developmental guidelines followed varied from game design-centered (Klopfer et al. 2005) to multimedia-focused (Salmi 2012) or center upon family inclusivity (Snyder and Elinich 2010). While design will certainly differ depending on the intended outcomes of the application, an accepted set of "best practices" in AR design could be beneficial. Findings from such research would provide both educators and curators important guidelines that, when taken into account, could lead to greater engagement with content and better foster learning from interaction with the exhibits. Furthermore, these results could lay the groundwork that would advocate for a greater acceptance and feeling of comfort when it comes to working with such a developing technology.

In addition to developmental understanding, it is also important that future research focus on gender differences when it comes to interacting with AR technology. As was previously noted, males and females traditionally have different responses to interaction with instructional games. For example, Bonanno and Kommers (2008) report that males are less apprehensive about gaming and feel more confident when using games than their female counterparts ($p < 0.016$). From our selected reports, Atwood-Blaine and Huffman (2017) also noted differences in perception of difficulty between male and female participants, an aspect that may lead to a dichotomy in the learning outcomes of visitors. Salmi et al. (2016) however noted no differences in achievement based on gender in their findings. Further insight into what could make AR technology more inclusive would be beneficial to maximize the learning environment. Likewise, it could be important to investigate how interactions with AR in an informal setting might change across age groups. Understanding the processes that contribute to learning with AR could also benefit the learning experience and aid ISE environments in reaching their intended educational goals. It would also be important for future research to focus on long-term educational outcomes and the sustainability of academic achievements. This is an aspect of AR use in informal environments that has often not been reported on in the literature and could be beneficial going forward. Understanding these differences in an AR learning environment could be paramount in the design of applications that maximize the ISE experience for everyone.

Conclusions

Recent national reports have noted a need for increased interest and engagement in the STEM disciplines in order to meet the critical future need for STEM graduates in the workforce (Brewer and Smith 2011; Olson and Riordan 2012). Informal science learning sites have been previously noted to provide visitors' opportunities to increase both interest and engagement in the STEM fields through interaction with exhibits and activities (Jensen and Lister 2016; Schwan et al. 2014; Tofield et al. 2003). Advances in technology have provided new opportunities for modification and enhancement of such aspects of informal STEM learning environments. This review of the use of AR in exhibit-based ISE settings focused primary published studies in order to gather information on the efficacy of these applications and to track the emergence of such a dynamic technology. The 17 studies included in this review investigated mainly topics that fell into the category of physical science or macroscopic life science. The two exceptions to this were one study that focused on a mathematics exhibit (Sommerauer and Müller 2014) and one that focused on a center-wide exploration application (Atwood-Blaine and Huffman 2017). Outcomes were consistent across all of the studies reviewed in that participants showed both an increase in conceptual knowledge and increases in topic interest and engagement. In the future, studies on the use of AR in informal learning environments would benefit from greater understanding of what learning theories and developmental strategies underlie these results and how they may aid in the formation of development guidelines for AR application design. Furthermore, information on experiential differences between genders and ages could aid in assuring the most effective outcomes from AR experiences. Results of this review point to the benefits of AR technology as part of informal STEM learning and provide evidence that technological advancements in informal settings can promote important aspects of learning such as engagement and collaboration. As the importance of informal learning sites in education continues to increase, the importance of the understanding of the technology incorporated in these environments will also become paramount. Findings of this review aim to inform the scientific community of the benefits and uses of AR technology in an informal learning environment as well as further its adoption and expansion in the future.

Funding This research was conducted with support from the National Science Foundation (Grant No. 1647131).

Compliance with Ethical Standards

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

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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