Computers & Education 62 (2013) 41–49

Contents lists available at SciVerse ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

Current status, opportunities and challenges of augmented reality in education

Hsin-Kai Wu [a,*], Silvia Wen-Yu Lee [b], Hsin-Yi Chang [c], Jyh-Chong Liang [d]

[a] Graduate Institute of Science Education, National Taiwan Normal University, PO Box 97-27, Taipei 11699, Taiwan
[b] Graduate Institute of Science Education, National Changhua University of Education, No. 1, Jin-De Road, Changhua 500, Taiwan
[c] Graduate Institute of Science Education, National Kaohsiung Normal University, No. 62, Shenjhong Rd., Yanchao District, Kaohsiung 82446, Taiwan
[d] Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology, No. 43, Sec. 4, Keelung Rd., Taipei 106, Taiwan

ARTICLE INFO

Article history:
Received 27 January 2012
Received in revised form
22 October 2012
Accepted 26 October 2012

Keywords:
Virtual reality
Architectures for educational technology system

ABSTRACT

Although augmented reality (AR) has gained much research attention in recent years, the term AR was given different meanings by varying researchers. In this article, we first provide an overview of definitions, taxonomies, and technologies of AR. We argue that viewing AR as a concept rather than a type of technology would be more productive for educators, researchers, and designers. Then we identify certain features and affordances of AR systems and applications. Yet, these compelling features may not be unique to AR applications and can be found in other technological systems or learning environments (e.g., ubiquitous and mobile learning environments). The instructional approach adopted by an AR system and the alignment among technology design, instructional approach, and learning experiences may be more important. Thus, we classify three categories of instructional approaches that emphasize the "roles," "tasks," and "locations," and discuss what and how different categories of AR approaches may help students learn. While AR offers new learning opportunities, it also creates new challenges for educators. We outline technological, pedagogical, learning issues related to the implementation of AR in education. For example, students in AR environments may be cognitively overloaded by the large amount of information they encounter, the multiple technological devices they are required to use, and the complex tasks they have to complete. This article provides possible solutions for some of the challenges and suggests topics and issues for future research.

1. Introduction

Bridging virtual and real worlds, augmented reality (AR) creates a reality that is enhanced and augmented (Bronack, 2011; Klopfer & Squire, 2008). New possibilities for teaching and learning provided by AR have been increasingly recognized by educational researchers. The coexistence of virtual objects and real environments allows learners to visualize complex spatial relationships and abstract concepts (Arvanitis et al., 2007), experience phenomena that is not possible in the real world (Klopfer & Squire, 2008), interact with two- and three-dimensional synthetic objects in the mixed reality (Kerawalla, Luckin, Seljeflot, & Woolard, 2006), and develop important practices and literacies that cannot be developed and enacted in other technology-enhanced learning environments (Squire & Jan, 2007; Squire & Klopfer, 2007). These educational benefits have made AR one of the key emerging technologies for education over the next five years (Johnson, Levine, Smith, & Haywood, 2010a, 2010b; Martin et al., 2011).

Although AR has garnered much research attention in recent years, the term AR was given different meanings by researchers. Additionally, AR could be created by utilizing and connecting various innovative technologies (e.g., mobile devices, wearable computers, and immersion technologies). However, like many innovations, the educational values of AR are not solely based on the use of technologies but closely related to how AR is designed, implemented, and integrated into formal and informal learning settings. To provide insights into opportunities offered by AR, therefore, the purpose of this article is to present current status, opportunities, and challenges of AR in education.

To achieve the purpose of this article, we sought empirical studies and theoretical papers that addressed questions of how AR could be designed for educational purposes and how AR could be incorporated into educational settings. Articles and book chapters published from

* Corresponding author. Tel.: +886 2 77346805; fax: +886 2 29333018.
E-mail addresses: hkwu@ntnu.edu.tw (H.-K. Wu), silviawyl@cc.ncue.edu.tw (S.W.-Y. Lee), hsinyichang@nknucc.nknu.edu.tw (H.-Y. Chang), aljc@mail.ntust.edu.tw (J.-C. Liang).

0360-1315/$ – see front matter
http://dx.doi.org/10.1016/j.compedu.2012.10.024

January 2000 to October 2012 in the database of Educational Resources Information Center (ERIC), Social Science Citation Index (SSCI) journals were included in our literature search. We chose keywords including: augmented reality, mixed reality, and education and obtained over 70 citations. We also searched for conference papers from the IEEE database, particularly those published in International Symposium on Mixed and Augmented Reality (ISMAR), for relevant papers. After the searches, we selected only those that focused on AR and related educational issues. This left us with a total of 54 citations. We then read these articles and chapters, discussed major findings, generated guiding questions for in-depth reading, and took notes on how the questions were answered in the papers. The guiding questions included: How does the paper define augmented reality? What are the functions and affordances of AR in education identified in the paper? Is there any framework, theory, or principle guiding the design of AR in the paper? How is AR integrated into learning or teaching (e.g., any associated learning or teaching activities)? What learning outcomes are promoted by AR? Several temporary themes emerged from our notes. After another round of reading and discussion, we summarized and analyzed the statements and arguments in the papers to support the themes and to accomplish our purpose.

In the following sections, we start with an overview of definitions, taxonomies, and technologies of AR. We argue that viewing AR as a concept rather than a type of technology would be more fruitful for educators, researchers, and designers. Then we identify features and affordances of AR systems and applications. Yet, these compelling features may not be unique to AR applications and can be found in other technological systems or learning environments (e.g., ubiquitous and mobile learning environments) with similar technologies. The alignment between technology design, instructional approach, and learning experiences may be more important when AR is implemented in classrooms. Thus, we propose three major categories of instructional approaches that have been employed in AR learning environments and discuss what and how AR helps students learn. While AR offers new learning opportunities, it brings challenges as well. We outline technological, pedagogical, and learning issues related to the implementation of AR in education and discuss possible solutions for some of the issues. Finally, based on our analyses and discussions of research in AR, directions for future research are suggested.

2. Definitions, taxonomies and technologies

2.1. Definitions of AR

Researchers in computer sciences and educational technology have defined AR diversely. Milgram, Takemura, Utsumi, and Kishino (1994) defined “augmented reality” by two approaches: a broad approach and a restricted approach. In the broad sense, AR refers to “augmenting natural feedback to the operator with simulated cues” (p. 283). On the other hand, the restricted approach emphasizes the technology aspect and is defining AR as “a form of virtual reality where the participant’s head-mounted display is transparent, allowing a clear view of the real world” (p. 283). There were also researchers defining AR based on its features or characteristics. For example, as proposed by Azuma (1997), AR can be defined as a system that fulfills three basic features: a combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects.

Klopfer (2008) indicated that the term AR should not be defined restrictedly. This term could be applied to any technology that blends real and virtual information in a meaningful way. According to Klopfer and Squire (2008), AR could be broadly defined as “a situation in which a real world context is dynamically overlaid with coherent location or context sensitive virtual information” (p. 205). In this situation, AR could provide users technology-mediated immersive experiences in which real and virtual worlds are blended (Klopfer & Sheldon, 2010) and users’ interactions and engagement are augmented (Dunleavy, Dede, & Mitchell, 2009).

For educators and designers, defining AR in a broad sense would be more productive because such a definition suggests that AR could be created and implemented by varied technologies, such as desktop computers, handheld devices, head-mounted displays and so on (Broll et al., 2008; Johnson et al., 2010b; Liu, 2009). That is, the notion of AR is not limited to any type of technology and could be reconsidered from a broad view nowadays. AR exploits the affordances of the real world by providing additional and contextual information that augments learners’ experience of reality (Squire & Klopfer, 2007). AR might be based on and accompany with technology, but it should be conceptualized beyond technology only.

2.2. Taxonomies of AR

As being defined as a situation, AR signifies a variation of virtual reality, and plays a supplemental role rather than a replacement of reality (Azuma, 1997; Martin-Gutierrez et al., 2010). To describe to what extent reality is supplemented or augmented, previous research has been developed several taxonomies of AR. Milgram et al. (1994) proposed a so-called Reality–Virtuality continuum, ranging from a completely real environment to a completely virtual one. Within this continuum, mixed reality can be defined as a situation where real world and virtual world objects are presented together. Moreover, mixed reality consists of two main ideas: augmented reality and augmented virtuality (AV). According to Milgram et al., AR is a combination of the real and the virtual and contains more real than virtual, whereas AV refers to adding elements of reality to a virtual environment and includes more virtual information. For example, virtual objects could be added to a real environment in AR, and a real object could be projected into a virtual environment in AV. Their differentiation might rely on whether reality or virtuality is being enhanced (Liu, Cheok, Mei-Ling, & Theng, 2007). Although the immersive learning environment, where virtual and real objects coexist in a seamless way, is advocated, the differentiations between AV and AR still need to be noticed. AR, therefore, can be regarded as mixed reality, which perhaps contains more real than virtual materials and information.

In addressing the issue of distinction between AV and AR, Klopfer (2008) further used a spectrum to emphasize the weight of the augmentation provided in AR. How much virtual information provided to the users determines the weight. A lightly augmented reality refers to a situation in which users utilize a large amount of information and physical materials from the real world, and have access to relatively little virtual information. On the other hand, a heavily augmented reality contains frequently accessible virtual information. This spectrum suggests a possible role of technology in augmented reality. In a heavily augmented world, most immersive technologies, such as head-mounted displays, are implemented. For lightly augmented reality, users mainly interact with physical materials and objects, and occasionally manipulate and access the virtual information. The mixed reality created by location-awareness mobile devices is one typical example (Klopfer & Yoon, 2005).

Moreover, to highlight the characteristics of AR, Broll et al. (2008) proposed a three-dimension framework consisting of "immersion" (from reality to virtual), "ubiquity" (stationary to omnipresent), and "multiplicity" (single user to potentially everyone). The "immersion" dimension equals to the reality-virtuality continuum (Milgram et al., 1994). The "ubiquity" dimension refers to the issues of how and where the system might be used, while "multiplicity" dimension involves the degree of usage by concurrent users. AR, thus, can be located at a middle point in each of the dimensions. This framework also provides guidance for design of an AR system that can be constructed by integrating various technologies.

2.3. Technologies of AR

Technology plays an important role in AR research. In some previous studies the term "technology" is part of the definition of AR. For example, Klopfer and Sheldon (2010) defined AR as a "technology" that blends real and virtual world experience. The aforementioned restricted approach views AR as a form of virtual reality with a head-mounted display (Milgram et al., 1994). This definition reflects the early development of AR technology that usually included head-mounted apparatus to overlay virtual information onto the real world. With a rapid evolution of technology, the AR concept could be further extended because more and more hardware and software devices could be utilized to create augmented reality. For instance, the advancements of handheld computing open new opportunities for augmented reality (Martin et al., 2011; Squire & Klopfer, 2007) and create a subset of AR: mobile-AR (Feng, Duh, & Billinghurst, 2008). The mobility offered by handheld devices would leverage the authenticity of a learning environment and increase learners' interactions with others (Klopfer & Sheldon, 2010). Additionally, mobile devices make pervasive AR systems possible (Broll et al., 2008). Instead of using head-mounted displays, pervasive AR systems run on handheld computers with location-registered technology (e.g., Global Positioning System [GPS]). Pervasive or mobile-AR systems are less obtrusive with a focus on real environments. Another application of AR is the combination of mixed realities and remote laboratories (Andújar, Mejías, & Márquez, 2011). By overlaying virtual elements on remote devices, students could remotely manipulate and interact with the real as well as virtual devices. Together these AR technologies allow ubiquitous learning enhanced by computer simulations, remote laboratories, physical models, and 3D or virtual objects (Broll et al., 2008; Dunleavy et al., 2009).

Then how can AR technologies be used for educational purposes? First, AR technologies help learners engage in authentic exploration in the real world, and virtual objects such as texts, videos, and pictures are supplementary elements for learners to conduct investigations of the real-world surroundings (Dede, 2009). One of the most prevalent uses of AR is to annotate existing spaces with an overlay of location-based information (Johnson et al., 2010a). Secondly, the use of AR technologies can extend to the integration of real-world and digital learning resources. As Klopfer and Squire (2008) showed, the usage of AR enables learners to experience scientific phenomena that are not possible in the real world (e.g., chemical reactions). Liu et al. (2007) introduced several AR systems that fall into this purpose; through explorations in AR, students were able to view the virtual solar system on the classroom table or to visualize the process of photosynthesis. Moreover, Kerawalla et al. (2006) founded that AR technologies have the potential to engage learners in manipulating virtual materials from a variety of perspectives. In the study by Kaufmann, Steinbugl, Dunser, and Gluck (2005), a 3D dynamic geometry system (Construct3D) aimed at facilitating mathematics and geometry education was developed. As an AR system, Construct3D not only provided students with a real-world setting to collaborate together, but also demonstrated virtual 3D objects for students to operate, measure, and manipulate in order to understand spatial relationships.

Although AR technologies involve high-end electronics and sophisticated tools, as Bronack (2011) argued, these technologies themselves are not important for educational researchers. More important is how the technologies support and afford meaningful learning. Considering AR as a concept rather than a certain type of technology would be more productive for educators, researchers, and designers. Thus, in the following section, we discuss features and affordances of AR for educational purposes.

3. Features and affordances

AR as a mixed and enhanced reality has compelling features for educational purposes; its potential and affordances can be further extended when an AR system is designed by connecting multiple types of technologies. In this section, we identify features and affordances of AR systems in five aspects based on research that exploits AR for educational purposes. According to the research, AR could enable (1) learning content in 3D perspectives, (2) ubiquitous, collaborative and situated learning, (3) learners' senses of presence, immediacy, and immersion, (4) visualizing the invisible, and (5) bridging formal and informal learning. We discuss each aspect as follows.

First, AR can enhance learning experiences by using 3D synthetic objects for students to interact with. AR enables students to use 3D synthetic objects to augment the visual perception of the target system or environment (Arvanitis et al., 2007). Students can inspect the 3D object from a variety of different perspectives to enhance their understanding (Chen, Chi, Hung, & Kang, 2011). Kerawalla et al. (2006) showed an example of using 3D AR in teaching astronomy. The study included two types of sessions: AR and traditional teaching sessions. In the AR session, teachers and elementary school students used a combination of technologies including a whiteboard, projector, web camera, AR tile, and virtual 3D modeling package to observe and rotate a virtual 3D spinning earth to learn about earth and sun, and day and night. The traditional teaching session included reading of a print book, lecture about the solar system, and a demonstration using 3D physical objects (e.g., a tennis ball, a string, and a torch) to learn the same topics. The authors analyzed the questions teachers asked in the two sessions and teachers' interviews after the sessions. They found that teachers realized the benefits of using 3D imagery and believed that AR can make inaccessible subject matter available to students. However, Kerawalla et al. did not compare whether the 3D learning experience created by AR was significantly more beneficial to students than the manipulation of real-world 3D physical models. Early research on chemistry education may provide insight into this question. Copolo and Hounshell (1995) found that students in the group of using both computer and physical models performed significantly better than the groups using either one of the models. Wu, Krajcik, and Soloway (2001) also argued that both computer and physical models "should be provided through class instruction because different students have preferences for different types of models and symbol systems" (p. 838). In terms of research in AR, more evidence is required to support for the use of the AR-based 3D virtual models over the real-world 3D models.

A second aspect of affordances relates to the use of handheld computers in AR. With mobile devices, wireless connection, and location-registered technology, the pervasive or mobile-AR system could enable ubiquitous, collaborative and situated learning enhanced by computer simulations, games, models, and virtual objects in real environments (Broll et al., 2008; Dunleavy et al., 2009). The affordances of such a system could include portability, social interactivity, context sensitivity, connectivity, and individuality (e.g., Klopfer, 2008; Squire & Jan, 2007; Squire & Klopfer, 2007). For example, several mobile-AR games such as Environmental Detectives (Klopfer, 2008; Squire & Klopfer, 2007) and Mad City Mystery (Squire & Jan, 2007) were developed to support learning outside of classrooms. In Environmental Detectives, students used handheld computers to conduct investigations, gathered data unique to the location, analyzed and interpreted the data, and proposed solutions sensitive to the context. Squire and Klopfer (2007) indicated that engaging students in playing virtual games in real spaces may raise students' context sensitivity, and result in making more informed decisions considering all environmental-related factors. Moreover, using handheld devices in mobile environments could cause students to be distracted and increase task interruptions (Nagata, 2003). Because an AR system could detect students' locations and working status, provide task reminders, and offer alternatives to refocus students' attention, these embedded attention-aware features may help decrease task interruptions and manage students' attention (Roda & Thomas, 2006). Additionally, social interactivity could be enhanced when students collaborate through networked mobile devices as well as face-to-face interactions (Birchfield & Megowan-Romanowicz, 2009), and scaffolding customized to different paths of investigations could be provided to promote individuality (Klopfer, 2008).

Thirdly, Bronack (2011) claimed that AR and other immersive media for learning such as serious games and virtual worlds offer affordances of presence, immediacy, and immersion. AR could provide a mediated space that gives learners a sense of being in a place with others. Such sense of presence may enhance students' recognition of community of learners (Squire & Jan, 2007). Additionally, an AR system could include real-time feedback and provide verbal and nonverbal cues to foster students' sense of immediacy (Kotranza, Lind, Pugh, & Lok, 2009). Given that immediacy is important to foster the affective side of learning, AR that brings together learners, virtual objects or information, and characters in a real environment have the potential to increase immediacy. Finally, immersive media like AR could provide learners with a sense of immersion, which is "the subjective impression that one is participating in a comprehensive, realistic experience" (Dede, 2009, p. 66). Dede (2009) also suggested that immersion could make possible the learning situated in real-world problems, issues and environments. A recent mobile-AR study builds on the AR affordances of enhancing learners' senses of presence, immediacy and immersion to support students' learning of a socio-scientific issue on nuclear energy use and radiation pollution in the context of the nuclear accidents at the Fukushima Daiichi Nuclear Power Plant after the 3.11 earthquake in Japan (Chang, Wu, & Hsu, 2012). Ninth graders used Android tablet computers to collect data of simulated radiation values on their campus, which was hypothetically a campus about 12 km away from the Nuclear Power Plant and hypothetically on the first day after the hydrogen gas explosion at the power plant. The study found a significant correlation between students' perceptions of the AR activity and change in nuclear attitudes, providing evidence that AR can possibly affect learners' affective domains toward real-world issues.

Another aspect of affordances is that AR superimposing virtual objects or information onto physical objects or environments enables visualization of invisible concepts or events (Arvanitis et al., 2007; Dunleavy et al., 2009). AR systems could support learners in visualizing abstract science concepts or unobservable phenomena, such as airflow or magnetic fields, by using virtual objects including molecules, vectors, and symbols. For example, Augmented Chemistry allowed students to select chemical elements, compose into 3D molecular models, and rotate the models (Fjeld & Voegtli, 2002). Clark, Dünser, and Grasset (2011) augmented a paper-based coloring book with 3D content and provided children with a pop-up book experience of visualizing the book content. These augmented real objects create new visualizations that have potential to enhance students' understanding of abstract and invisible concepts or phenomena.

A fifth aspect of affordances identified from the literature is that AR has the potential to bridge the gap between learning in formal and informal settings. For example, the CONNECT project employed AR and other technologies to develop a virtual science thematic park environment (Sotiriou & Bogner, 2008). The environment had two modes: the museum mode and school mode. Scenarios developed in the environment include both virtual and conventional field trips to science museums, pre- and post-visit curricular activities, and experiment and modeling activities. In this project, therefore, science learning at school was connected to learning experiences of the virtual and conventional museum visits, with the use of AR to augment students' visualization, experiments and models. An initial evaluation of the CONNECT project indicated that the environment positively influenced students' intrinsic motivation for learning science and conceptual understanding of the friction concept (Sotiriou & Bogner, 2008).

However, the compelling features and affordances identified in this section may not be unique to AR, because some of them could be found in other systems or environments (e.g., ubiquitous and mobile learning environments) with similar technologies or concepts. To exploit the affordances of AR, thus, it is important to explore how the use of AR could be aligned with different instructional approaches in order to achieve proposed educational objectives (Bronack, 2011). Below we present and categorize instructional and learning approaches that have been adopted in creating AR learning environments and implementing the concept of AR in varying educational settings.

4. Instructional and learning approaches

A variety of instructional and learning approaches have been taken in the design of AR learning environments, including game-based learning (Rosenbaum, Klopfer, & Perry, 2007; Squire & Jan, 2007; Squire & Klopfer, 2007), place-based learning (Klopfer, 2008; Mathews, 2010), participatory simulations (Klopfer & Sheldon, 2010; Rosenbaum et al., 2007; Squire & Klopfer, 2007), problem-based learning (Liu, Tan, & Chu, 2009; Squire & Klopfer, 2007, p. 375), role playing (Rosenbaum et al., 2007), studio-based pedagogy (Mathews, 2010), and jigsaw method (Dunleavy et al., 2009). Different subsets of AR (e.g., mobile-AR, game-based AR, and multiplayer AR) offer different affordances to support the implementation of these approaches. Based on the most salient features of the approaches, we classify the instructional approaches into three major categories: approaches emphasizing engaging learners into "roles," approaches emphasizing learners' interactions with physical "locations," and approaches emphasizing the design of learning "tasks." It is of note that each approach may include several learning approaches, and that some sub-approaches may overlap. Also, approaches across different categories may share a similar philosophical ground or an educational psychology point of view.

4.1. Emphasizing the "roles"

Approaches emphasizing engaging learners into different roles in an AR environment included participatory simulations, role playing, and jigsaw approach. Because these approaches emphasize the interactions and collaboration among students, they are usually associated with mobile-AR, multiplayer AR, or game-based AR. Participatory simulations can be defined as allowing "different players to function as interacting components of a dynamic system" and consequently interactions among students affect the outcomes of the system (Klopfer & Squire, 2008, p. 225). An illustrative example of participatory simulations can be found in the Virus game in which students played viruses in the process of infectious disease transmission (Klopfer, Yoon, & Rivas, 2004). Students beamed information to each other through handheld devices to simulate the process of infecting each other. Additionally, in some AR environments, students have distinct roles to play in order to develop in-depth understanding about a topic. For instance, in Squire and Klopfer (2007), students were assigned to identities of environmental investigators, scientists, and environmental activists to understand the socially situated nature of scientific investigations. Students not only took part in a simulated system but also adopted different ways of thinking or had access to information relevant to their roles while playing the different roles. Furthermore, a jigsaw approach focuses on collaborations among different roles so that students could complete tasks through role playing. In this kind of design, students who play different roles are given unique pieces of information. It relies on collaboration or jigsaw among different roles of a team to solve a problem together (Dunleavy et al., 2009).

4.2. Emphasizing the "locations"

Place-based or location-based learning emphasizes learners' interactions with the physical environment so mobile-AR with location-registered technology is a common subset used for this approach. AR environments that take these approaches exploit the advantages of mobile technologies because mobile devices make it possible for computer servers to track learners' actual geological location (e.g., De Lucia, Francese, Passero, & Tortora, 2012). Through mobile devices and geological positioning systems, learners have access to relevant information as they arrive at certain locations (Klopfer, 2008). The place or location for AR can be, for instance, a school campus where students actually study or the actual neighborhood where the school is located.

One of the potential benefits of place-based learning is to bring a sense of authenticity to students. Students may feel more grounded in "reality" as they work in a physical area or move through an actual environment (Rosenbaum et al., 2007). Also, when becoming familiar with the actual environment and making informed decisions about environmental issues are important learning goals, they can be realized by having students collect data or investigate issues at different locations of the actual environment. However, a common challenge of place-based learning is that students need to cope with the constraints of the actual environment (Klopfer, 2008).

4.3. Emphasizing the "tasks"

The third category is centered on the design of learning tasks in AR environments. The approaches that can be identified in this category are: game-based, problem-based, and studio-based learning. Because of the diverse nature of the tasks, the implementation of these approaches does not necessarily rely on a specific subset of AR technologies. Among the approaches, game-based learning is one of the most popular for AR. AR games can be defined as "games played in the real world with the support of digital devices that create a fictional layer on top of the real world context" (Squire & Jan, 2007, p. 6). Features of game-based learning include roles, activities centered around challenges, sites for contested spaces, and authentic resources and tools embedded in the system (Squire & Jan, 2007). Even though the feature of inhabiting roles is overlapped with the role-playing approach, other features distinguish game-based learning from the approaches emphasizing the roles of learners. Games, usually including one or a series of tasks, have been characterized as a combination of fun, challenge, and curiosity. A game provides digital information to one or more players, takes and processes input from the players, and changes the digital information provided to the players based on the input (Kirriemuir & McFarlane, 2003). For instance, in an AR game called Outbreak @ The Institute (Rosenbaum et al., 2007), students worked together to prevent further spread of an infectious disease. The different roles in the game included doctors, medical technicians, and public health experts. Students could gather information through interacting with virtual characters and by acquiring virtual data from authentic resources and tools embedded in the system.

Another task-based approach is problem-based learning. This approach is employed to promote self-directed learning, self-motivation, problem-solving skills, and knowledge-application skills (Liu et al., 2009). Although the learning goals of problem-based learning and game-based learning are usually different, one approach may embed another in the design of tasks and activities. For instance, many AR games included problem-solving features in the design (e.g., Squire & Klopfer, 2007). In Liu et al. (2009), students played games prior to the problem-solving tasks; both game-based and problem-based activities were included within the learning module but in different learning phases. Somehow in the design of AR learning activities, the boundary between real-life problem solving and game-like problem solving can be blurry.

Studio-based learning also emphasizes the nature of learning tasks and focuses on learning by design, through which students design and author their own augmented reality games (Mathews, 2010). This approach starts with project-based work on open-ended problems and follows by frequent iterations of design and evaluation (Kafai, 1995). The fundamental notion for studio-based learning is that students, as designers, learn about design, content, and skills as they go through the tasks in the design process. For example, in Mathews (2010), high students from an interdisciplinary language arts and social studies classroom used mobile devices to identify and research issues in their community, and then designed games about the identified issues individually and collaboratively. Finally, they designed GPS-based AR games on mobile devices to teach other students and community members about the issues.

It is our observation that the design of AR learning environments usually involves more than one instructional approach. For instance, an AR learning environment can be designed in a game context, adapting location-based learning, and also using participatory simulation (Rosenbaum et al., 2007; Squire & Klopfer, 2007). By employing appropriate instructional approaches, AR environments could exploit affordances of augmented reality, align with expected learning goals, and influence how and what students learn.

5. Learning effects

What and how do students learn in AR learning environments? Research has indicated that AR systems and environments could help learners develop skills and knowledge that can be learned in other technology-enhanced learning environments but in a more effective way (El Sayed, Zayed, & Sharawy, 2011). El Sayed et al. (2011) used AR systems to present lessons in a 3D format so learners could virtually manipulate a variety of learning objects and handle the information in a novel and interactive way. AR environments can also facilitate skill acquisition. In Klopfer (2008), AR mobile games allowed learners to organize, search and evaluate data and information; therefore, learners' skills in navigating primary and secondary data could be developed through these games.

A new set of skills that are important and essential in an information-based economy can also be promoted in AR learning environments (Mathews, 2010; Rosenbaum et al., 2007). For example, Rosenbaum et al. (2007) showed that the sense of authenticity offered by an AR learning environment promoted learners' understanding of dynamic models and complex causality. Furthermore, AR environments could increase students' motivation and interest, which in turn may help them develop better investigation skills and gain more accurate knowledge on the topic (Sotiriou & Bogner, 2008). Specifically, students' spatial abilities can be improved after using immersive and collaborative AR applications (Kaufmann & Schmalstieg, 2003; Kaufmann et al., 2005; Martin-Gutierrez et al., 2010). Various teacher–student interaction scenarios could also be supported by AR systems, thus maximizing transfer of learning (Dede, 2009; Kaufmann & Schmalstieg, 2003). Another new set of skills that could probably be promoted in AR are psychomotor-cognitive skills because AR could make use of visual cues as well as haptic cues to enhance users' experiences (Feng et al., 2008). Kotranza et al. (2009) showed an AR system in clinical medicine that embedded touch-sensors in a physical environment, collected sensor data to measure learners' performances, and then transformed the performance data into visual feedback. By using this AR system, learners could receive real time, in-situ responses that may help improve their performances and enhance their psychomotor skills in a cognitive task.

Additionally, AR systems provide solutions for learning difficulties that have been identified in previous research. For example, students usually encounter difficulties visualizing unobservable phenomena such as spinning of the earth (Kerawalla et al., 2006). AR allows learners to manipulate virtual objects or observe phenomena that may not be easily seen in a natural environment (e.g., ecosystems of wetland or life cycles of wetland creatures). These learning experiences in turn could promote learners' thinking skills and conceptual understandings about invisible phenomena (Liu et al., 2009) and correct their misconceptions (Sotiriou & Bogner, 2008). Although so far a majority of AR systems have been developed for teaching science and mathematics because learning these subjects require visualization of abstract concepts, there were also a few systems designed for students with special needs and language learning. For instance, Liu (2009) constructed an AR learning environment with a context-aware learning game to help students overcome learning barriers and effectively improve learners' English speaking and listening skills.

Furthermore, AR environments promote important practices and literacies that may not be developed and enacted in other technology-enhanced learning environments (Squire & Jan, 2007; Squire & Klopfer, 2007). The AR game in Squire and Jan (2007) provided students with opportunities to experience how scientists think and do, and to apply their scientific understandings to resolve current issues happening in their local community. Squire and Klopfer (2007) also suggested that AR games could activate learners' prior knowledge, connect prior knowledge to the physical world, and engage students in academic content and practices.

Although using AR for teaching and learning seemed promising, some research indicated negative effects on learning such as low engagement (Kerawalla et al., 2006). Kerawalla et al. found that while teachers recognized the benefits of using an AR system in classrooms, they would like to have more control over the content in the system so they could adapt the needs of their students. This suggests that, like many emerging innovations, AR provides new possibilities as well as challenges. In the next section, we discuss technological, pedagogical, and learning issues related to the implementation of AR in education and provide possible solutions for some of the issues.

6. Technological, pedagogical, and learning issues

6.1. Technological issues

As mentioned previously, one type of AR technologies includes a head-mounted display and/or an additional backpack with computer equipment. The cumbersome and expensive design could cause problems such as discomfort and poor depth perception (Kerawalla et al., 2006). To avoid these problems, current development of AR systems adopts portable technologies that are less obtrusive and enhance a sense of immersion and presence. Yet, these systems integrate several hardware and software devices and lead to issues like interfacing between multiple devices (Klopfer & Squire, 2008) and stability of the devices (Dunleavy et al., 2009; Squire & Jan, 2007). Without well-design interfaces or protocols to guide students' actions, students could have difficulties in interpreting the clues in the devices and the real-world environment, recognizing the information flow from one device to another, and navigating between fantasy and reality (Squire & Jan, 2007).

Additionally, the more the devices used, the greater the risk of device failure. How to maintain high stability of multiple devices becomes critical. In Dunleavy et al. (2009), GPS errors caused students' frustration and were identified by teachers as a highly problematic issue. Fortunately, the issues of device integration and stability could be solved by the recent rapid advancement in portal and wireless technologies. In addition to more than a dozen of software applications, a tablet PC or a smartphone could include a built-in video camera, GPS, wireless receiver, faster processor, and large hard-drive memory. It can be expected that the portable devices in AR systems will be more and more integrated and reliable when running simulations, games, videos, and GPS applications.

Another issue is regarding a tradeoff in technology design between location dependency and independency (Klopfer & Sheldon, 2010). While location-specific technologies contextualize students' learning, provide a connection to a particular location, and help students give new meaning to their familiar locations, location-independent design has advantages in portability and flexibility that does not require teachers and students to be present in specific locations and could save great cost on transportation. To balance the two approaches, educators and designers may consider a design that not only connects to real-world locations but also includes important features that can be commonly found in other locations (Klopfer & Sheldon, 2010). TimeLab 2100 is an example that integrates portability with location specificity and provides generic real-world locations (e.g., a school and a bus stop) so students could find local substitutes for their learning needs.

6.2. Pedagogical issues

There are also pedagogical issues that need to be taken into consideration when AR systems are implemented in classrooms. First, like many educational innovations in the past, the use of AR in classrooms could encounter constraints from schools and resistances among teachers. The learning activities associated with AR usually involve innovative approaches such as participatory simulations and studio-based pedagogy. The nature of these instructional approaches however is quite different from the teacher-centered, delivery-based focus in conventional teaching methods (Kerawalla et al., 2006; Mitchell, 2011; Squire & Jan, 2007). Institutional constraints such as covering a certain amount of content within a given time frame also cause difficulties in implementing innovations (Kerawalla et al., 2006). Thus, there may be a gap between the teaching and learning methods currently used in classrooms and the students-centered and exploratory nature of learning engendered by AR systems. Designers of AR learning environments need to realize the gap and provide possible support to help teachers and students bridge it.

A second issue involves instructional design. In the design of learning activities and AR systems, how should the information be distributed and flowed between two realities and among different devices? As Klopfer and Squire (2008) indicated, "how to balance competing drives for individuality with distribution and decentralized information flows with guided educational activities may be tensions central to the platform" (p. 205). A set of design guidelines based on learning theories (e.g., distributed cognition and situated learning) and empirical evidence would be useful for educators and designers to resolve this tension.

Another pedagogical issue is regarding the inflexibility of the content in AR systems (Kerawalla et al., 2006). In some AR systems, the content and the teaching sequence are fixed; teachers are not able to make changes to accommodate students' needs or to accomplish instructional objectives. This issue could be resolved by the use of authoring tools (Bergig, Hagbi, El-Sana, & Billinghurst, 2009), which allow teachers and students to revise and create AR activities and applications (Klopfer & Squire, 2008).

6.3. Learning issues

There are also challenges related to learners and their learning processes. In an AR learning environment, students could be cognitively overloaded by the large amount of information they encounter, the multiple technological devices they are required to use, and the complex tasks they have to accomplish. That is, students need to be multitasking in AR environments. Dunleavy et al. (2009) reported that students often felt overwhelmed and confused when they were engaged in a multi-user AR simulation because they had to deal with unfamiliar technologies as well as complex tasks.

Additionally, the tasks in AR environments may require students to apply and synthesize multiple complex skills in spatial navigation, collaboration, problem solving, technology manipulation, and mathematical estimation (Dunleavy et al., 2009). Previous research indicated that one reason for students' learning challenges in AR environments lies in a lack of these essential skills (Kerawalla et al., 2006; Klopfer & Squire, 2008; Squire & Jan, 2007). Particularly for younger learners and novices at conducting open-ended investigations, additional scaffolding and support would be necessary to help them generate an appropriate plan of action, search for possible solutions to their problem, and interpret clues provided by the technological devices and embedded in the real-world environment (Klopfer & Squire, 2008).

Furthermore, AR provides a situation where reality and fantasy are blended but this mixed reality could cause students' confusions. In Klopfer's (2008) study, some students "lose sight of where the game ends and reality begins" (p. 100). Even though such confusion signals the authenticity of an AR system, losing track of the real environment may not be productive for learning and could result in a threat to students' physical safety (Dunleavy et al., 2009).

7. Directions for future research

As presented in previous sections, our analyses and discussions of empirical studies in AR indicated that while augmented reality can be created by integrating multiple technologies and has a great potential to support learning and teaching, there are various issues to consider when AR is implemented in educational settings. Additionally, these empirical studies have limitations in terms of research design and evidential validity. In this section, we identify limitations in previous research, suggest research topics and issues that need to be explored, and conclude with directions for future research.

Compared to studies of other more mature technologies in education (e.g., multimedia, and web-based platforms), research of AR applications in education is in an early stage, and evidence of the effects of AR on teaching and learning appears to be shallow. Through years of empirical studies, research on the use of computer or Internet in education has come to understand the relationships between learners' characteristics and technology use, and has already shown some effectiveness of technologies in promoting learning outcomes (e.g., Lee et al., 2011). Many studies of AR still focused on development, usability, and initial implementation of AR tools (Argotti, Davis, Outters, & Rolland, 2002; Blake & Butcher-Green, 2009; El Sayed et al., 2011; Kaufmann & Schmalstieg, 2003). Also, what stands out as a theme among the empirical studies in AR is that the research design of these studies is relatively simple, short-term, small-sample in exploratory nature. Several studies were at an early stage of development and relied on learners' self-reports of usability, preference, and efficiency to evaluate the learning effects, such as studies of ARSC (El Sayed et al., 2011), Construct3D (Kaufmann & Schmalstieg, 2003), and CONNECT (Arvanitis et al., 2007). Additionally, the methods used are mainly design-based research (Klopfer & Squire, 2008) and case studies (Dunleavy et al., 2009; Squire & Klopfer, 2007). Only a few are exceptions, such as the quasi-experimental design employed in Kaufmann and Schmalstieg (2003), Hsiao, Chen, and Huang (2012), and Liu (2009).

Therefore, to provide more evidence on the educational values of AR, controlled and comprehensive evaluation studies that include a large sample and valid instrumentation are needed. Additionally, to highlight the features and affordances of AR, researchers should also continue identifying effective curricular and technology characteristics that can be offered by AR but not possible with other learning media or concepts to reveal educational values unique to AR learning environments. The empirical evidence from these studies could inform theories and help generate a set of instructional patterns and design principles of AR environments that could provide guidance to resolve the issues involved in instructional design. For example, Enyedy, Danish, Delacruz, and Kumar (2012) outlined two design principles for design augmented reality activities in learning physics: (1) Using embodied play and participatory modeling to support science inquiry, and (2) Supporting progressive symbolization within rich semiotic ecologies to construct meaning. Yet, they also acknowledged that their one-group pretest–posttest design did not allow them to systematically investigate some aspects of their design and intended to employ other experimental designs to provide more evidence to justify their principles. Other productive research topics include identifying instructional factors and conditions that affect the effectiveness of an AR system (e.g., Sotiriou & Bogner, 2008) and examining the role of individual differences in learning with AR (e.g., Chen & Tsai, 2012).

Table 1
Possible alignments of instructional approaches, affordances, and notions in education.

Instructional approaches	Affordances	Notions
Emphasizing “roles”	(3)[a] Learners’ senses of presence, immediacy, and immersion	Engagement
Emphasizing “locations”	(2) Ubiquitous, collaborative and situated learning (5) Bridging formal and informal learning	Contextualization
Emphasizing “tasks”	(1) Learning content in 3D perspectives (4) Visualizing the invisible	Authenticity

[a] The numbers follow the numbering of the affordances in the section of Features and affordances.

Furthermore, future research that includes in-depth analyses of how AR environments support learning and teaching creates opportunities for researchers to re-conceptualize important notions in education such as contextualization, authenticity, and engagement. Table 1 suggests possible alignments of instructional approaches, affordances and notions in education. Approaches emphasizing engaging learners into different roles in an AR environment included participatory simulations and role playing. These AR environments emphasize learners’ participation in different roles and could enhance the sense of presence, immediacy, and immersion. For example, role playing in AR allows students to feel being there and provides comprehensive, realistic experiences that can only be achieved in a mixed reality. These learning experiences could lead to new forms of behavioral, emotional, and cognitive *engagement* (Wu & Huang, 2007) that need to be documented and theorized in educational research.

Additionally, location-based learning approaches emphasize learners’ interactions with the physical environment. As mentioned previously, the implementation of the location-based approaches and mobile technologies in AR could bridge the gap between formal and informal learning and afford ubiquitous, collaborative and situated learning (Table 1). The alignment of location-based instructional approaches with the affordances of AR could result in a reconceptualization of *contextualization* that has been defined as “utilization of particular situations or events that occur outside of class or are of particular interest to students” (Rivet & Krajcik, 2008, p. 80). Because the combination of location-based learning and AR technologies blurs the boundaries between inside and outside of the classroom and between formal and informal learning settings, where a context is and what it means by contextualization may be re-defined.

Features of the task-based learning approaches could also be enhanced by AR, because it could change the nature and lower the complexity of learning tasks by showing the content, tasks, or problems in different perspectives and making invisible become observable (Table 1). By doing so, an inauthentic task may be transformed into an authentic one because a well-designed AR environment could help learners relate the task to the real world and create new meanings for them. To what extent a task is authentic needs a re-thought because personal and real-world *authenticity* could be fluid and changeable over time in an AR learning environment (Shaffer & Resnick, 1999).

There are also research topics and issues regarding instructional design and implementation waiting to be explored. As mentioned previously, a majority of AR systems were designed for teaching science and mathematics, so future research requires the development of substantial educational content on AR for other learning subjects. More educational studies with solid research design and rigorous analysis are needed to examine the learning effects of AR. In addition, the potential of AR could be further expanded by designing and implementing it for different educational purposes (e.g., assessments and tutoring) with diverse populations such as students with special needs and life-long learners. Moreover, because of the gap between the conventional teaching methods in classrooms and the exploratory nature of learning engendered by AR systems, researchers need to explore the possibilities and solutions of integrating AR into regular school curricula. One solution may be providing substantial support for teachers to tailor AR technologies, to create customized learning activities, and to monitor students’ learning progress in AR.

Acknowledgment

This study was based upon work supported by the National Science Council of Taiwan under NSC 100-2511-S-003-041-MY3 and the Aim for the Top University Project at the National Taiwan Normal University. We would like to thank Dr. Chin-Chung Tsai for his help and thoughtful comments on the paper.

References

Andújar, J. M., Mejías, A., & Márquez, M. A. (2011). Augmented reality for the improvement of remote laboratories: an augmented remote laboratory. *IEEE Transactions on Education, 54*(3), 492–500.

Argotti, Y., Davis, L., Outters, V., & Rolland, J. P. (2002). Dynamic superimposition of synthetic objects on rigid and simple-deformable real objects. *Computers & Graphics, 26*(6), 919–930. http://dx.doi.org/10.1016/S0097-8493(02)00180-2.

Arvanitis, T. N., Petrou, A., Knight, J. F., Savas, S., Sotiriou, S., Gargalakos, M., et al. (2007). Human factors and qualitative pedagogical evaluation of a mobile augmented reality system for science education used by learners with physical disabilities. *Personal and Ubiquitous Computing, 13*(3), 243–250. http://dx.doi.org/10.1007/s00779-007-0187-7.

Azuma, R. T. (1997). A survey of augmented reality. *Presence-Teleoperators and Virtual Environments, 6*(4), 355–385.

Bergig, O., Hagbi, N., El-Sana, J., & Billinghurst, M. (2009, October). *In-place 3D sketching for authoring and augmenting mechanical systems* (pp. 87–94). Paper presented at the 8th IEEE international symposium on mixed and augmented reality (ISMAR), Orlando, FL. http://dx.doi.org/10.1109/ISMAR.2009.5336490.

Birchfield, D., & Megowan-Romanowicz, C. (2009). Earth science learning in SMALLab: a design experiment for mixed reality. *International Journal of Computer-supported Collaborative Learning, 4*(4), 403–421. http://dx.doi.org/10.1007/s11412-009-9074-8.

Blake, M. B., & Butcher-Green, J. D. (2009). Agent-customized training for human learning performance enhancement. *Computers & Education, 53*(3), 966–976. http://dx.doi.org/10.1016/j.compedu.2009.05.014.

Broll, W., Lindt, I., Herbst, I., Ohlenburg, J., Braun, A. K., & Wetzel, R. (2008). Toward next-gen mobile AR games. *Computer Graphics and Applications, IEEE, 28*(4), 40–48. http://dx.doi.org/10.1109/MCG.2008.85.

Bronack, S. C. (2011). The role of immersive media in online education. *Journal of Continuing Higher Education, 59*(2), 113–117. http://dx.doi.org/10.1080/07377363.2011.583186.

Chang, H.-Y., Wu, H.-K., & Hsu, Y.-S. (2012). Integrating a mobile augmented reality activity to contextualize student learning of a socioscientific issue. *British Journal of Educational Technology*, . http://dx.doi.org/10.1111/j.1467-8535.2012.01379.x.

Chen, C.-M., & Tsai, Y.-N. (2012). Interactive augmented reality system for enhancing library instruction in elementary schools. *Computers & Education, 59*(2), 638–652. http://dx.doi.org/10.1016/j.compedu.2012.03.001.

Chen, Y.-C., Chi, H.-L., Hung, W.-H., & Kang, S.-C. (2011). Use of tangible and augmented reality models in engineering graphics courses. *Journal of Professional Issues in Engineering Education and Practice, 137*(4), 267–276.

Clark, A., Dünser, A., & Grasset, R. (2011, October). *An interactive augmented reality coloring book* (pp. 259–260). Paper presented at the 10th IEEE international symposium on mixed and augmented reality (ISMAR), Basel, Swiss. http://dx.doi.org/10.1109/ISMAR.2011.6143487.

Copolo, C. F., & Hounshell, P. B. (1995). Using three-dimensional models to teach molecular structures in high school chemistry. *Journal of Science Education and Technology, 4*(4), 295–305.

Dede, C. (2009). Immersive interfaces for engagement and learning. *Science, 323*(5910), 66–69. http://dx.doi.org/10.1126/science.1167311.

De Lucia, A., Francese, R., Passero, I., & Tortora, G. (2012). A collaborative augmented campus based on location-aware mobile technology. *International Journal of Distance Education Technologies, 10*(1), 55–73. http://dx.doi.org/10.4018/jdet.2012010104.

Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of Science Education and Technology, 18*(1), 7–22. http://dx.doi.org/10.1007/s10956-008-9119-1.

El Sayed, N. A. M., Zayed, H. H., & Sharawy, M. I. (2011). ARSC: augmented reality student card – an augmented reality solution for the education field. *Computers & Education, 56*(4), 1045–1061. http://dx.doi.org/10.1016/j.compedu.2010.10.019.

Enyedy, N., Danish, J. A., Delacruz, G., & Kumar, M. (2012). Learning physics through play in an augmented reality environment. *International Journal of Computer-supported Collaborative Learning, 7*(3), 347–378. http://dx.doi.org/10.1007/s11412-012-9150-3.

Feng, Z., Duh, H. B.-L., & Billinghurst, M. (2008 September). *Trends in augmented reality tracking, interaction and display: A review of ten years of ISMAR*. Paper presented at the 7th IEEE/ACM international symposium on mixed and augmented reality (ISMAR), Cambridge, UK. http://dx.doi.org/10.1109/ismar.2008.4637362.

Fjeld, M., & Voegtli, B. M. (2002, September). *Augmented chemistry: An interactive educational workbench* (pp. 259–321). Paper presented at the international symposium on mixed and augmented reality (ISMAR), Darmstadt, Germany. http://dx.doi.org/10.1109/ISMAR.2002.1115100.

Hsiao, K.-F., Chen, N.-S., & Huang, S.-Y. (2012). Learning while exercising for science education in augmented reality among adolescents. *Interactive Learning Environments, 20*(4), 331–349. http://dx.doi.org/10.1080/10494820.2010.486682.

Johnson, L. F., Levine, A., Smith, R. S., & Haywood, K. (2010a). Key emerging technologies for elementary and secondary education. *Education Digest, 76*(1), 36–40.

Johnson, L. F., Levine, A., Smith, R. S., & Haywood, K. (2010b). Key emerging technologies for postsecondary education. *Education Digest, 76*(2), 34–38.

Kafai, Y. B. (1995). *Minds in play: Computer game design as a context for children's learning*. Mahwah, NJ: Lawrence Erlbaum.

Kaufmann, H., & Schmalstieg, D. (2003). Mathematics and geometry education with collaborative augmented reality. *Computers & Graphics, 27*(3), 339–345. http://dx.doi.org/10.1016/s0097-8493(03)00028-1.

Kaufmann, H., Steinbugl, K., Dunser, A., & Gluck, J. (2005). General training of spatial abilities by geometry education in augmented reality. *Cyberpsychology & Behavior, 8*(4), 330.

Kerawalla, L., Luckin, R., Seljeflot, S., & Woolard, A. (2006). "Making it real": exploring the potential of augmented reality for teaching primary school science. *Virtual Reality, 10*(3), 163–174.

Kirriemuir, J., & McFarlane, A. E. (2003). *Literature review in games and learning*. Bristol, England: Nesta Futurelab.

Klopfer, E. (2008). *Augmented learning: Research and design of mobile educational games*. Cambridge, MA: MIT Press.

Klopfer, E., & Sheldon, J. (2010). Augmenting your own reality: student authoring of science-based augmented reality games. *New Directions for Youth Development, 128*, 85–94. http://dx.doi.org/10.1002/yd.378.

Klopfer, E., & Squire, K. (2008). Environmental detectives: the development of an augmented reality platform for environmental simulations. *Educational Technology Research and Development, 56*(2), 203–228. http://dx.doi.org/10.1007/s11423-007-9037-6.

Klopfer, E., & Yoon, S. (2005). Developing games and simulations for today and tomorrow's tech savvy youth. *TechTrends, 49*(3), 33–41.

Klopfer, E., Yoon, S., & Rivas, L. (2004). Comparative analysis of palm and wearable computers for participatory simulations. *Journal of Computer Assisted Learning, 20*(5), 347–359. http://dx.doi.org/10.1111/j.1365-2729.2004.00094.x.

Kotranza, A., Lind, D. S., Pugh, C. M., & Lok, B. (2009, October). *Real-time in-situ visual feedback of task performance in mixed environments for learning joint psychomotor-cognitive tasks* (pp. 125–134). Paper presented at the 8th IEEE international symposium on mixed and augmented reality (ISMAR), Orlando, FL. http://dx.doi.org/10.1109/ISMAR.2009.5336485.

Lee, S. W.-Y., Tsai, C.-C., Wu, Y.-T., Tsai, M.-J., Liu, T.-C., Hwang, F.-K., et al. (2011). Internet-based science learning: a review of journal publications. *International Journal of Science Education, 33*(14), 1893–1925. http://dx.doi.org/10.1080/09500693.2010.536998.

Liu, T.-Y. (2009). A context-aware ubiquitous learning environment for language listening and speaking. *Journal of Computer Assisted Learning, 25*(6), 515–527. http://dx.doi.org/10.1111/j.1365-2729.2009.00329.x.

Liu, T.-Y., Tan, T.-H., & Chu, Y.-L. (2009). Outdoor natural science learning with an RFID-supported immersive ubiquitous learning environment. *Educational Technology & Society, 12*(4), 161–175.

Liu, W., Cheok, A. D., Mei-Ling, C. L., & Theng, Y.-L. (2007). *Mixed reality classroom: Learning from entertainment*. Paper presented at the proceedings of the 2nd international conference on digital interactive media in entertainment and arts, Perth, Australia.

Martin, S., Diaz, G., Sancristobal, E., Gil, R., Castro, M., & Peire, J. (2011). New technology trends in education: seven years of forecasts and convergence. *Computers & Education, 57*(3), 1893–1906. http://dx.doi.org/10.1016/j.compedu.2011.04.003.

Martin-Gutierrez, J., Saorin, J. L., Contero, M., Alcaniz, M., Perez-Lopez, D. C., & Ortega, M. (2010). Design and validation of an augmented book for spatial abilities development in engineering students. *Computers & Graphics, 34*(1), 77–91. http://dx.doi.org/10.1016/j.cag.2009.11.003.

Mathews, J. M. (2010). Using a studio-based pedagogy to engage students in the design of mobile-based media. *English Teaching: Practice and Critique, 9*(1), 87–102.

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1994). Augmented reality: a class of displays on the reality–virtuality continuum. *Proceedings the SPIE: Telemanipulator and Telepresence Technologies, 2351*, 282–292.

Mitchell, R. (2011). Alien contact!: exploring teacher implementation of an augmented reality curricular unit. *Journal of Computers in Mathematics and Science Teaching, 30*(3), 271–302.

Nagata, S. F. (2003). Multitasking and interruptions during mobile web tasks. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 47*(11), 1341–1345, doi:10.1177/154193120304701105.

Rivet, A. E., & Krajcik, J. S. (2008). Contextualizing instruction: leveraging students' prior knowledge and experiences to foster understanding of middle school science. *Journal of Research in Science Teaching, 45*(1), 79–100. http://dx.doi.org/10.1002/tea.20203.

Roda, C., & Thomas, J. (2006). Attention aware systems: theories, applications, and research agenda. *Computers in Human Behavior, 22*(4), 557–587. http://dx.doi.org/10.1016/j.chb.2005.12.005.

Rosenbaum, E., Klopfer, E., & Perry, J. (2007). On location learning: authentic applied science with networked augmented realities. *Journal of Science Education and Technology, 16*(1), 31–45. http://dx.doi.org/10.1007/s10956-006-9036-0.

Shaffer, D. W., & Resnick, M. (1999). "Thick" authenticity: new media and authentic learning. *Journal of Interactive Learning Research, 10*(2), 195–215.

Sotiriou, S., & Bogner, F. X. (2008). Visualizing the invisible: augmented reality as an innovative science education scheme. *Advanced Science Letters, 1*, 114–122. http://dx.doi.org/10.1166/asl.2008.012.

Squire, K., & Jan, M. (2007). Mad city mystery: developing scientific argumentation skills with a place-based augmented reality game on handheld computers. *Journal of Science Education and Technology, 16*(1), 5–29. http://dx.doi.org/10.1007/s10956-006-9037-z.

Squire, K., & Klopfer, E. (2007). Augmented reality simulations on handheld computers. *Journal of the Learning Sciences, 16*(3), 371–413. http://dx.doi.org/10.1080/10508400701413435.

Wu, H.-K., & Huang, Y.-L. (2007). Ninth grade student engagement in teacher-centered and student-centered technology-enhanced learning environments. *Science Education, 91*, 727–749. http://dx.doi.org/10.1002/sce.20216.

Wu, H.-K., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching, 38*(7), 821–842. http://dx.doi.org/10.1002/tea.1033.