Augmented Reality Learning Experiences: Survey of Prototype Design and Evaluation

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Abstract—Augmented reality (AR) technology is mature for creating learning experiences for K-12 (pre-school, grade school, and high school) educational settings. We reviewed the applications intended to complement traditional curriculum materials for K-12. We found 87 research articles on Augmented Reality Learning Experiences (ARLEs) in the IEEE Xplore Digital Library and other learning technology publications. Forty-three of these articles conducted user studies, and seven allowed the computation of an effect size to the performance of students in a test. In our meta-analysis, research show that ARLEs achieved a widely variable effect on student performance from a small negative effect to a large effect, with a mean effect size of 0.56 or moderate effect. To complement this finding, we performed a qualitative analysis on the design aspects for ARLEs: display hardware, software libraries, content authoring solutions and evaluation techniques. We explain that AR incur three inherent advantages: real world annotation, contextual visualization, and vision-haptic visualization. We illustrate these advantages through the exemplifying prototypes, and ground these advantages to multimedia learning theory, experiential learning theory and animate vision theory. Insights from this review are aimed to inform the design of future ARLEs.

Index Terms—augmented reality learning experience, evaluation method, learning theory, meta-analysis, prototyping

1 Introduction

Technology affordances affect instructional design and the manner of teaching. Aside from the content, Dede [30] argues that the technological media (such as computers) have affordances which change the learning experience. Thus, it is important to study the effects of integrating technology in educational settings, and how such technologies can be maximized to improve learning. In an attempt to show whether or not people learn better with technology, Tamim et al. [103] conducted a second-order meta-analysis of technological approaches (using computers for word processing, computer-assisted instruction, distance education, simulation and hypermedia) against computer-free approaches to learning. Based on 25 meta-analyses representing 1055 primary studies for the past 40 years, Tamim et al. have shown that technology slightly to moderately improve student performance (effect size = 0.35).

1.1 Objectives

The development of Augmented Reality (AR) and related technologies enabled the creation of AR educational content. Progress in hardware computing power, real-time tracking, graphics rendering, and AR authoring tools contributed to applications that are already usable in educational settings. As a first goal, this paper aims to measure the effect of AR educational content to show whether or not it is useful.

Although there are many educational AR prototypes in the current literature, only a few are developed by interdisciplinary groups and base their work on learning theory. Even if the current state-of-the-art execution of AR educational content is effective, it can only be replicated to other contexts if a guideline exists for applying AR for education. As a second goal, we provide a guideline for effective AR content by first summarizing the state-of-the-art implementation and evaluation of AR prototypes. Then, we enumerate the affordances of AR for learning and discuss learning theories relevant to future AR educational content.

1.2 Organization

The rest of the paper is organized as follows: Section 2 proposes our definition of Augmented Reality and Augmented Reality Learning Experiences (ARLEs). Section 3 describes our methods for meta-analysis and qualitative analysis. Section 4 discusses the result of our meta-analysis of the effect of AR applications in educational settings. We attribute these effects to the use of natural affordances of AR technology and the use of design strategies. Section 5 discusses the results of our qualitative analysis of ARLEs covering the state-of-the-art implementation (display and content) techniques and evaluation techniques. Section 6 proposes a theoretical basis for the unique affordances of AR interaction,

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starting from theories of human cognition to theories of learning. Lastly, Section 7 concludes the paper with our recommendation for future educational AR prototypes.

2 Background

2.1 Augmented Reality

Augmented reality (AR) offers a different set of affordances from the various technological interventions. Thus, AR will be used differently from other technologies when it is applied to learning experiences. AR can be maximized in terms of improving learning experiences by leveraging on its natural capabilities.

Before reviewing applications of AR, we need to define AR. Azuma [9] defines AR to be when ”3-D virtual objects are integrated into a 3-D real environment in real time.” First, it requires the combination of virtual elements and real environment. It is helpful to think of AR as part of a virtuality continuum conceptualized by Milgram and Kishino [68]. On one side of the virtuality continuum is the purely real environment, and on the other side is the purely virtual environment. AR sits between these two extremes. The second AR requirement is three-dimensional registration such that the virtual elements are aligned to the real environment. The third AR requirement is real-time interactivity with the virtual elements. Thus, the virtual elements must behave like a real element in the real environment. This may mean, but is not limited to, the AR system responding to changes in the perspective of the user, changes in lighting conditions, occlusion and other physical laws.

When applied strictly to the current literature, whether or not an application adheres to the requirements is debatable. Many applications do not use 3D virtual objects. Instead, they add 2D images on flat surfaces like table-tops and books. Furthermore, many applications do not have perfect integration or 3D registration. The quality of implementation of integration in the current literature varies from imitating the effect of AR [96] to a full integration in an outdoor environment [104]. In the former, the effect of AR is simulated only by flashing relevant information on a screen. It does not employ any kind of tracking. Still, the author uses AR as a keyword. On the other hand, [104] is able to integrate a virtual butterfly on a real leaf. This is very difficult due to the dynamics of outdoor lighting.

2.2 Augmented Reality Learning Experiences

Augmented Reality, as a next-generation interface, affords a different way of interaction with information. This interaction can be used to design better learning experiences. We define the term Augmented Reality Learning Experiences (ARLEs) to refer to learning experiences facilitated by AR technology. For this review, the definition of AR by Azuma is relaxed to accommodate more prototypes that could help us understand how AR can be used for education. The works of Chang et al. [18], Lee [55], Billinghurst and Duenser [12] discuss some of the notable ARLEs for pre-school, grade school and high school education.

Chang et al. enumerates the many applicable contents that ARLE may facilitate. In his paper, he talks about examples of ARLEs for various subjects like physics, chemistry, geography and mathematics, as well as, educational games for primary education. Aside from these contents, Lee notes the use of ARLEs for astronomy, biology, geometry and cultural heritage. Billinghurst and Duenser explain that these kinds of content depend on the abilities of AR to:

1. illustrate spatial and temporal concepts,
2. emphasize contextual relationships between real and virtual objects,
3. provide intuitive interaction,
4. visualize and interact in 3D,
5. facilitate collaboration.

For example, the work of Matsutomo et al. [66] created an ARLE that demonstrates the five abilities of AR mentioned by Billinghurst and Duenser. In their ARLE, virtual magnetic fields were integrated with painted blocks acting as magnets (Figure 1). Students can move the magnets around to see how various positions would affect the shape of the magnetic fields. In this example, the space covered by a magnetic field and its variation in time is illustrated. The magnetic field moves with its magnet and changes its shape as it nears another magnet. The block magnets themselves can be moved by hand providing tangible interaction which is very natural for students. Lastly, this kind of system allows face-to-face collaboration wherein students can discuss the learning material in front of them.

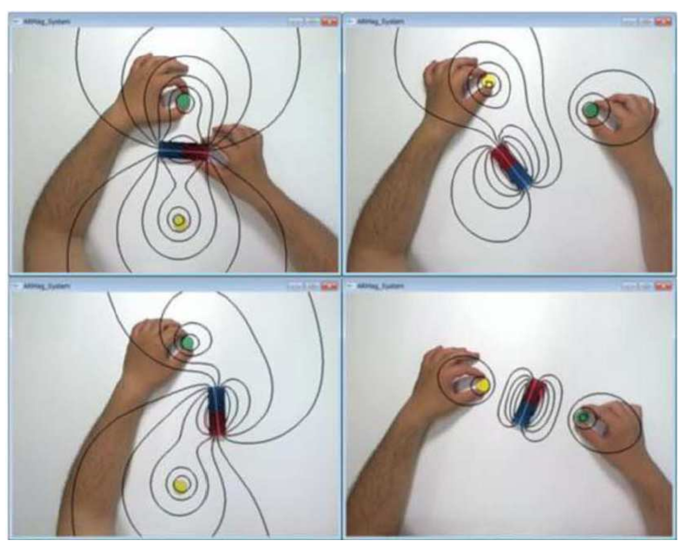

Fig. 1. ARLE by Matsumoto et al. [66] demonstrating the five abilities of AR that designers can leverage on. Virtual lines representing magnetic field lines are augmented onto blocks.

2.3 Design Factors

There are three factors affecting ARLE design. The factor may be hardware-related, software-related, or content-related. All these are inter-related with each other from the point of view of an ARLE application.

2.3.1 Hardware

The hardware dictates the computing power, and the physical interface, both the kind of display and the kind of input that can be accommodated. ARLEs mainly use desktop computers or smartphones as an AR device. Researchers using desktop computers as the platform have three options for the display namely a computer monitor, an overhead projector, or a head-mounted display. The choice of device alone affects which software and content would be appropriate. On one hand, desktop systems have bigger screens and higher computing power. On the other hand, a smartphone is more personal and more mobile. We discuss some examples of content and appropriate target displays in Section 5.1.

2.3.2 Software

The software design is about maximizing the computing power of the hardware, as well as managing content display and handling user inputs. The unique aspects of real-time tracking and 3D rendering are mostly achieved using open-source or commercial AR libraries. This aspect of AR is mature enough to enable ARLEs. Their further development in the future will directly benefit the creation of ARLEs. Currently, there are many open-source and commercial AR development kits suitable for many types of platforms. Among those mentioned in ARLEs are: ARToolkit (FLARToolkit, NyARToolkit), Eyesweb, HUMANAR, Junaio, Opira Registration Library, Popcode, Wikitude, and Zooburst.

2.3.3 Content

Content-related issues would be instructional design, authoring tools, and content management tools. This survey focuses on exploring learning theories as basis for effective learning experiences through AR. It discusses the design practices in the current literature to identify what has worked for other researchers. Instructional design is largely affected by the authoring tools available. Authoring tools are interfaces that allow a teacher to create a learning experience. In cases wherein the teacher is not familiar with programming (the more common case), simple authoring tools are necessary which would allow a teacher to select and load virtual information on a real environment. Design practices, related learning theories and authoring tools are discussed in Sections 4, 6 and 5.2, respectively.

Content management tools are tools that handle the content from storage to delivery to the device. ARLE content can be stored in the desktop PC itself. In cases wherein the desktop PC is in a network, some prototypes have used a server internal to the school. In the case of some commercial AR development kits, a service for hosting the virtual data is made available. Delivering location-aware content to handheld AR is a big technical challenge. However, there are existing solutions that are already explored under the fields of mobile learning (m-learning) and adaptive hypermedia. Existing technologies such as the Hewlett-Packard Mediascape Toolkit (mscape) can be used to design systems that deliver location-aware content [100]. Li et al. implemented a visual interactive mobile learning system that can fetch multimedia content by sending an image of a real object or by entering a predefined geographical area [57]. Moreover, Chang et al. have explored on an architecture for fetching relevant data to a target learning object in its natural environment. Their goal is to provide location-adaptive mobile ARLE [19]. In the remote education context, [16] discusses one-to-many remote video learning infrastructure wherein not only do the students receive lectures from the teacher, they can also receive AR content that they can view at home using a simple set up involving a handheld device and printed markers.

3 METHODS

3.1 Meta-analysis

We conducted a systematic literature review based on the work of Schmid et al. [91]. Their meta-analysis aimed to measure the impact of technology integration to outcomes in higher education. Their analysis of 315 effect sizes (from 231 primary studies) show that the effects associated with technology have not changed substantially over the years. The mean effect size of technology applied to higher education remains to have a wide variability around 0.28 or low to moderate effect. The methodology for the systematic literature review is as follows:

3.1.1 Search for Prototypes

A literature search was conducted in May 30, 2012, in the IEEE Xplore Digital Library. The search string used was: ("augmented reality") AND (educat* OR instruct* OR learn* OR teach* OR train*). To complement the candidate articles found in the IEEE Xplore Digital Library, the search string "augmented reality" was used to search the publications listed by the Centre of Learning Sciences and Technologies in [1]. Most of the 74 journal titles were searchable through the following online bibliographic databases:

1. EdITLib Digital Library,
2. IATED Digital Library,
3. Inderscience,
4. Sage Journals,
5. ScienceDirect,
6. Springer,
7. Taylor & Francis Online,
8. Wiley Online Library.

The search is limited to journal articles and conference proceedings that are written in English, and are accessible before June 2012. A total of 503 articles (458 conference proceedings, 42 journal and magazines, 3 early access articles) resulted from this initial search in the IEEE Xplore Digital Library. Another 150 articles were retrieved from other online bibliographic databases.

3.1.2 Inclusion Criteria

The focus of this survey is ARLEs for pre-school, grade school and high school education. Thus, for the research paper to be included, the following criteria must be met:

1. The research paper must have at least a preliminary working ARLE prototype.
2. The prototype should be applied to learning a new concept or skill.
3. The content should be relevant to kindergarten, primary and/or secondary education. (However, content need not be tested on these target students.)
4. The full research paper is publicly accessible.
5. The paper reports an effect size or provided a means to calculate the effect size (reports both mean and standard deviation).

Applying these criteria resulted in 7 articles.

3.1.3 Data Gathering

We computed an effect size using the formula:

$$d = \frac{\bar{x}_e - \bar{x}_c}{s} \tag{1}$$

where $\bar{x}_e$ is the mean of the experimental treatment, $\bar{x}_c$ is the mean of the control, and s is the pooled standard deviation:

$$s = \frac{\bar{s}_e + \bar{s}_c}{2} \tag{2}$$

where $\bar{s}_e$ is the standard deviation of the experimental treatment, $\bar{s}_c$ is the standard deviation of the control.

We interpret the calculated effect size based on Cohen's recommendation, that is, an effect size of 0.8 or higher is considered large, around 0.5 is considered moderate, and around 0.2 is considered small.

3.2 Qualitative Analysis

3.2.1 Search for Prototypes and Inclusion Criteria

We conducted the same search as in section 3.1.1 and applied the same inclusion criteria as in section 3.1.2 except the fifth criterion requiring an effect size. Relaxing the inclusion criteria resulted in 87 articles, with 62 articles found in the IEEE library. Note that these 87 articles do not represent 87 unique prototypes because a small fraction of these papers discusses advances in the development of the same prototype.

Moreover, not all these prototypes strictly adhere to the definition of AR: integrating 3D virtual objects onto a 3D real environment in real-time. For the purposes of gathering experiences in implementing and evaluating AR prototypes, we have decided to include the prototypes that make use of 2D images instead of 3D virtual objects. We also included prototypes that simulate the effect of AR but did not implement the tracking of the target object which is necessary to consider it as an integration of real and virtual elements.

3.2.2 Data Gathering

A survey questionnaire was drafted to facilitate the gathering of data from the 87 included articles. The questionnaire has four main parts namely:

1. publication details,
2. prototype description,
3. use of AR,
4. design and results of the user study.

The publication details refer to the title of paper, name of authors, name of publications, etc. The prototype description covers hardware, software, and content descriptions.

The use of AR refers to the possible functions of technology and the natural affordances of AR. Schmid et al. [91] listed some of the primary functions of technology in the education setting. For example, technology is commonly used to enrich and/or increase the efficiency of content presentation. The works of Brill and Park [15], and Blalock and Carringer [13] identify some natural affordances of AR as exemplified in the previous literature. For example, many AR applications use the annotation capability of AR to rapidly and accurately identify objects in the real world.

The design and results of the user study refer to the description of the control and experimental groups, the phenomena being measured, the effect of AR on that phenomena, etc. Aside from the performance of students in pre-tests and post-tests, other aspects of the learning experience such as motivation and satisfaction are usually observed.

The survey was designed to easily recognize common trends in the included papers, and to support further data gathering about the trends that have emerged. Whether or not an ARLE performs a particular function, or takes advantage of a particular AR affordance is debatable because of the diversity of ARLEs and the lack of details included in the research article. However, the goal is not to correctly decide whether or not a particular ARLE has a particular function or uses a certain affordance, but to gather enough examples of prototypes that are helpful in illustrating the possible functions and affordances of AR in the learning process. Further closer analysis was conducted after these example prototypes were identified.

The clarity of the survey was evaluated by having two researchers use it separately on 20 papers out of the 87 that pass the inclusion criteria. There were only minor misunderstandings of the questionnaire and these were clarified before proceeding to reading the remaining 67 papers. Each of the 67 papers was read only by one researcher.

4 Meta-analysis Results

Eleven articles evaluated their prototypes by conducting experiments to compare the performance of students who use their system versus a non-AR based approach. Seven of these articles allow the computation of an effect size. The seven AR applications for the educational setting, and their corresponding effect sizes are summarized in Table 1. The four additional articles that conducted other student performance evaluation are listed in Table 2. ARLEs achieved a widely variable effect on student performance ranging from a small negative effect to a large effect. The mean effect size is 0.56 which is higher than the reported mean effect of technology (d = 0.35 or slight to moderate effect).

4.1 Affordances of Augmented Reality

The researchers designed their ARLE to take advantage of the affordances of AR technology. These affordances are derived from the very nature of AR: the real-time integration of virtual elements to a real environment. By the definition, augmented reality affords:

1. Real world annotation - to display text and other symbols on real world objects; E.g. [43] annotates a real moving ball with values of velocity and the corresponding graph.
2. Contextual visualization - to display virtual content in a specific context; E.g. [22] uses AR to teach library skills by adding virtual information to a library.
3. Vision-haptic visualization - to enabled *embodied interactions* with virtual content. E.g. [63] allows the user to view a 3D model on a marker which he can manipulate using his hands.

4.2 Design Strategies

Aside from the natural affordances of AR, design strategies have been applied to the creation of more effective ARLEs. In ARLEs, researchers have used the following strategies:

1. Enable exploration - designing AR content that is non-linear and encourages further study; E.g. [56] allows students to try out different kinds of scenario of collision of two balls and see if the collision will happen in the way they hypothesize it to be.
2. Promote collaboration - designing AR content that requires students to exchange ideas; E.g. In [76], students were given different roles and tasked to negotiate with each other to arrive at a solution.
3. Ensure immersion - designing AR content that allows students to concentrate more and be engaged at a constant level. E.g. In [31], students were able to concentrate more using AR as opposed to a standard slide presentation.

4.3 Recommendation

The mean effect size of 0.56 of ARLEs to student performance should be taken critically. On one hand, it is a good snapshot of the effect of AR technology when used in educational settings. However, we must not think of AR as homogeneous interventions in the learning process given that it has a wide design space. The seven articles presented in Table 1 includes different display devices, content, and experimental design. Moreover, reading these papers individually also reveals that factors such as instructional design may have played a crucial role in the success of the ARLE.

It can be argued that factors such as learning objectives, pedagogy, teaching expertise, subject matter, grade level, consistency of use of technology, and factors other than the augmented reality intervention may have greater influence on the effect sizes [103]. However, as Dede [30] had argued, technology has affordances that affect how the content is designed. The changes in instructional design may either be because of imperfect control of the variables, or because of the technology used. Thus findings should be interpreted carefully, and should only be used as a guide given the variable effect sizes and the very small sample size of seven papers.

For future ARLEs, we recommend that researchers do the following:

1. Measure learning that can be attributed to ARLEs. There must be an experimental group who will receive the technological intervention, and there should be a proper control group. Factors such as instructional design, pedagogical approaches and teaching practices should be carefully controlled so that only the augmented reality intervention is made variable. Imperfections in controlling these aspects should be taken into account in the interpretation of the results. A heuristic for this is to ensure that *both the AR approach and the AR-free approach are both the best possible design for the particular content*.
2. Report both the mean and standard deviation of the performance of students. From these values, an effect size can be reported to measure the relative effect of the augmented reality intervention.
3. Apply the affordances and advantages of AR as needed by the educational setting. Augmented reality is multi-faceted and we have conducted a parallel qualitative study (Section 5) to complement the findings of our meta-analysis. AR involves a variety of devices, interactions, and applications that can be taken advantage of in creating learning experiences.

5 Qualitative Analysis Results

Eighty-seven papers were found in the current literature when the inclusion criteria were applied to the initial search result. The graph in Figure 2 shows the distribution of the publication year of these papers. Starting

TABLE 1
Studies Evaluating Student Performance With Effect Sizes

Ref.	Year	Content	Participant (Sample)	Control Group	Experimental Treatment	Effect Size (Average)
[58]	2009	English	Grade School, Teachers (67)	Printed material and audio material	AR situated learning around the campus	1.00
[43]	2010	Kinematics graphs	High School (80)	didactic teaching	Physics props are annotated with measurements and graphs using AR.	0.86
[63]	2010	Spatial ability	University students (49)	No spatial ability training using AR	With spatial ability training using AR	0.70, 0.72 (0.71)
[31]	2012	Renaissance art	High School (69)	Lecture with slides	AR annotated print out replicas of art pieces	0.67
[56]	2011	Elastic collision	University students (36)	Non-AR instructional material	Collaborative AR learning wherein students simulate collision.	0.33, 0.83 (0.58)
[41]	2011	English	Grade School (Six classes)	Lecture using audiovisual data	AR learning using magic book	0.37
[22]	2012	Library skills	Grade School (116)	Librarian teaches in the library	AR situated learning in the library	-0.28

TABLE 2
Other Studies Evaluating Student Performance

Ref.	Year	Content	Participant (Sample)	Control Group	Experimental Treatment	Result
[98]	2010	Solar system	High School (40)	Reading the textbook and teaching aid	AR learning using magic book	Increase by 29%
[76]	2009	Math game	Grade School (123)	Board game version of AR game	On-location AR game	No Significant Difference
[69]	2012	Eulerian graphs	University students (20)	notebook; handouts; tablet pc;	Note-taking on top of projected AR	No Difference
[32]	2006	Spatial ability	High School (215)	Geometry classes	Collaborative AR learning wherein students interact and explore 3D shapes	No Significant Difference

2007, there is an increasing number of papers discussing ARLE prototypes. This review included papers published before June 2012, as such it does not include papers from July to December, 2012. Of these 87, 72 are conference papers, whereas 15 are journal articles; 61 are indexed by IEEE Xplore, whereas the other 26 are found in other digital libraries.

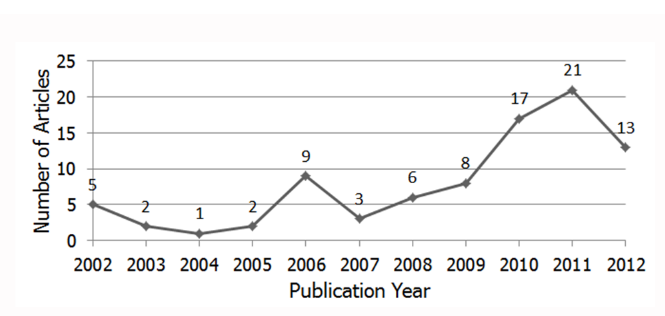

Fig. 2. ARLE publications per year until June 2012.

5.1 Display Metaphors

Choosing the appropriate display is an important design decision. In the current literature, there are four types of ARLE systems by the device used for display namely computer monitor, handheld device (smartphone, tablet, etc.), overhead projector, and head-mounted display. Table 3 lists display devices with exemplifying ARLEs and their corresponding contents.

Researchers have also distinguished the displays as either using a *mirror metaphor* or *glasses metaphor*. In [95] and [88], researchers have made this distinction as perspectives. The glasses metaphor is a 1st person perspective or AR that is based on what the user can see in front of him. On the other hand, the mirror metaphor is a 3rd person perspective wherein the user becomes an observer of himself. We can say that it is a matter of which real environment is being augmented: in front of the user, or directed towards the user.

5.1.1 *Mirror Metaphor*

The mirror metaphor is when a screen appears to be a reflection facing the user, except the user can also see the virtual images integrated to his or her reflection. Figure 3 (left) shows an example of the mirror metaphor. We

TABLE 3
Sample ARLES with Corresponding Display Devices

Display	Ref.	Content
Desktop monitor	[31]	Visual art pieces
	[14]	Human anatomy
	[34]	Chemistry concepts
Handheld devices	[104]	Butterfly life cycle
	[36]	Electrical circuit
	[49]	Architectural history
	[37]	Physical education
Overhead Projector	[87]	Spelling
	[108]	Playing the drums
Head-mounted display	[82]	Chinese characters
	[98]	Solar system
	[47]	Endangered animals

see the reflection of the person as well as the virtual information (vertebral column).

Fig. 3. Mirror metaphor (left) the where real environment used is behind the user [14]; and Glasses Metaphor (right) where the real environment used is in front of the user [104].

Desktop computers are used for the mirror metaphor ARLEs. The mirror metaphor has been applied in ARLEs to provide students with compelling learning experiences. For example, Blum et al. 2012 [14] used the mirror metaphor in presenting an x-ray-like application wherein the user is given an illusion of being able to see inside his body through a computer screen. This kind of system would be useful for students studying human anatomy and sports science to help them connect their understanding of human movements and muscles. In this type of application, the mirror metaphor becomes advantageous since the content is about studying the human body itself.

5.1.2 *Glasses Metaphor*

The glasses metaphor refers to displays wherein a user appears to be looking into the world with a pair of special glasses. In this case, virtual information is integrated to what the user sees in front of him. Figure 3 (right) shows an example of the glasses metaphor. Three devices have been applied for ARLEs under the glasses metaphor:

1. Head-mounted Display - In [98], Sin and Zaman used the glasses metaphor to present virtual heavenly bodies on AR markers which they can manipulate in front of them. Students wore a head-mounted display so that both of their hands would be free to handle the markers containing the virtual solar system. A similar study by Shelton and Hedgely [95] had argued that this visualization is advantageous because students can more easily understand concepts such as day and night when they can test for themselves what happens when one side of the earth is occluded.
2. Handheld - In the work of Tarng and Ou [104], students can view virtual butterflies in a real school garden to understand the butterfly life cycle. In this case wherein students need to move around an area, the use of handheld devices is advantageous because all the processing, data connectivity and display are found in one light-weight device. Some researchers point out that nowadays, many people own smartphones and tablets which are ideal for indoor and outdoor AR experiences. These handheld devices are equipped with fast processors, graphics hardware, large touchscreens, and various sensors like camera, GPS, compass and accelerometer [12].
3. Projector - Projector-based AR affords more user movement in a confined space, say a room, than using desktop systems with monitors. However, it does not afford as much movement as in handheld AR. The display of projector-based AR is bigger than computer monitors and smartphone screens. The projector-based system have been successfully used to create a training system for playing a drum set [108], wherein, the drums are annotated with signals for when to hit the drums. Researchers have pointed out that desktop computers and overhead projectors are already available in most schools making them economical for ARLEs.

5.2 Content Creation

The main concern in creating AR content for ARLEs are authoring tools and instructional design. Developers of ARLEs usually use AR libraries such as the ARToolkit to create the prototype. However, teachers need authoring tools that would allow them to create content without having to be proficient in programming.

According to Wang et al. [107], authoring tools for non-programmers can be low-level or high-level. Low-level tools require some coding or scripting skills, whereas, high-level tools use visual authoring techniques. Both types usually would make use of drag and drop interfaces as well as menus. Currently, there are several authoring tools for any type of AR application targeting non-programmers such as DART, ComposAR, AMIRE and MARS which are discussed briefly in [107]. A basic authoring tool would be BuildAR [107] which allows the teacher to scale, translate and position virtual objects with respect to a fiducial marker. For example, virtual art pieces can be displayed in a real room to create an AR museum experience [102].

5.2.1 *Magic Book*

In the current literature, some researchers have developed ways to author AR content for learning. Researchers are exploring mainly three kinds of educational material namely, magic books, learning artefacts and location-based content. Researchers consider the book metaphor as one of the main modes of how AR will be used in education [12]. Using the book as the real element, additional virtual content can be added onto it using AR making it a magic book. Students are already familiar with books which afford many natural ways of interaction like flipping pages and viewing the book at different perspectives. For example, the work of Jee et al. [41] and [42] talks about an authoring tool for markerless books. The work of Vate-U-Lan [106] used a commercial authoring tool, Zooburst [4], for making an ARLE based on the magic book metaphor.

5.2.2 *Learning Artefact*

Another trend in the current literature is the use of learning artefacts, wherein students can learn about a particular object. Rahman et al. [84] developed an authoring tool that would allow a teacher to present a small object on a camera, and annotate it with virtual information using a live video visualization. Aside from a desktop PC, they used a depth camera to capture the color image and corresponding depth information. They used the ”polygonal annotation scheme” wherein the teacher could draw a polygon on the screen where he or she could see the object he or she wants to annotate with information.

In [97], Simeone and Iaconesi have pre-trained a system to recognize parts of a sculpture called the Minkisi. Users can then annotate virtual information on the real parts of the Minkisi via a desktop system. They describe their use case to involve multiple types of users such as curators, teachers and students. Each of them can annotate information on specific parts of the artefact based on various online sources. Users can then evaluate each other’s information based on accuracy and usefulness. Thus, content is developed through a process of communication among the different author-consumer with the physical object as the central point of conversation. Figure 4 shows the Minkisi and the two parts where students can annotate information.

5.2.3 *Location-based Content*

Location-based game is an emerging learning technology that takes advantage of providing relevant information to a place such as buildings and artefacts. Researchers

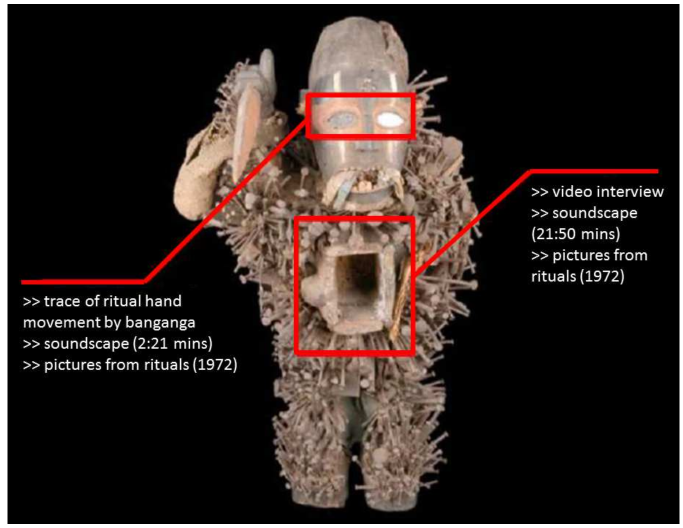

Fig. 4. The Minkisi artifact and the parts of interest [97]. Systems can be trained to recognize parts of an object, which later on can be augmented with information, making the object the locus of discussion.

have shown that novel e-learning experiences can be provided by delivering content relevant to a place (e.g. history). Chang et al. [20] have demonstrated this using handheld devices equipped with RFID tag readers and GPS positioning to deliver information regarding objects found in the real world. Although the game itself represents most of the pedagogical design, AR is an effective display for learners because it integrates the virtual information directly onto the target real world object. Moreover, AR has the advantage of using the camera for detecting and tracking an object in the real world, as opposed to using RFID readers which are not readily available in handheld devices. Furthermore, putting RFID tags on the real world may not be feasible in cases wherein objects should not be touched such as some historical artefacts.

ARLEs can offer location-based content usually used for outdoor AR experiences with handheld devices. Klopfer and Sheldon [52] have developed the AR Game-Builder that allows teachers to create educational AR mobile games in a specific locality. Their system offers predefined maps and GPS coordinates to place virtual objects such as characters in a specific place in the world. According to Klopfer and Sheldon, their platform also encourages students to transfer an existing game, to another place such as their own city; or even create their own game.

5.2.4 *Collaborative Content*

AR authoring itself is seen as an educational experience. For example, Billinghurst and Duenser have used BuildAR to let students create their own AR scene. In this process, students develop skills such as math abilities, drawing digital content, and telling stories. In this use case, it is important that the authoring tool is easy enough even for grade school students to use. In the case of the prototype of Simeone and Iaconesi, the content is developed in a conversational style wherein the cultural artefact becomes the locus of the discussion. Students could verify each other's inputs by researching, and teachers can be able to focus the discussion of the class based on the learning objectives.

The prototype by Odeh et al. 2012 [73] allows students to add virtual wires onto a real circuit and conduct experiments. Such systems make the student feel the reality of components and instruments used in an engineering experiment without the students physically accessing the laboratory. Moreover, the remote laboratory is available to them for much longer time than a regular laboratory.

Lastly, Klopfer and Sheldon have tested the AR GameBuilder and the students have successfully used it for creating linear games which involve both technical skills and creative writing. Table 4 summarizes some authoring tools that have been used for authoring ARLEs.

TABLE 4
Authoring Activities in ARLEs

Ref.	Authoring Activity
[74]	Students can add virtual wires on a real circuit in a remote laboratory set up.
[41], [42]	Teachers can author e-learning applications using a markerless magic book metaphor.
[97]	Teacher, students and the curator can all access and add information related to a cultural artefact.
[24]	Real props for physics classes such as balls, carts and rods are augmented with virtual information such as text and arrows.
[52]	Teachers and students can create and access educational games using predefined maps and GPS coordinates, virtual characters, and file management support.
[102]	Teachers can make a web-based virtual museum by selecting 3D models, associating them to markers, and arranging them in a room.
[84]	Allows a video annotation approach in order to catalogue and add virtual information on physical learning artefacts in a scene.
[99]	The CONNECT Visual Designer allows educators to specify the interactions the learner can have within the AR environment by creating rule-based scenarios.

5.2.5 *Architecture*

Learning objects - "any entity, digital or non-digital, that can be used, reused, or referenced during technology supported learning" [25] - can be used as the model for packaging and distributing ARLE content. In [90], Santos et al. recommends thinking of ARLE content to have three internal components that can be edited to make it adaptable to multiple educational settings. The first component is the context which refers to the target object or environment. The second component is the digital content which includes 3D graphics, annotative words and symbols, and images. The last component is the instructional activity. For example, the work [52] allows teachers and students to author, and re-author a location-based game. The context is the initial real place of the game with landmarks in the real world. The digital content are GPS coordinates, virtual characters, etc. The instructional activity is the game itself. Such game was made adaptable into a different context or a different real place in the world by allowing teachers and students to have re-authoring capabilities. Teachers or students themselves can make changes in the digital content such as moving virtual characters. Therefore, one location-based game designed for one city can be adapted into a different city.

5.2.6 *Instructional Design*

Aside from authoring tools, instructional design is also an important consideration in building ARLEs. To adapt ARLEs in formal education, a special curriculum should be designed to carefully integrate the use of AR and its various accompanying devices into classroom use. In [65], Mathison and Gabriel suggest three stages in introducing ARLE to an existing curriculum. The assumption is that the students have never used special devices and AR technology before to learn a concept. The objective of the first stage is to teach the student skills such as exploration, investigation and evaluation using the chosen AR display such as smartphones and desktop computers. The next stage is to introduce the capabilities of AR such as the allowed interactions. Lastly, the students can now experience the ARLE, as well as, build their own AR experience. Furthermore, Mathison and Gabriel, recommends a carefully designed day-to-day curriculum that would state the learning objective, AR time allocation, AR experience, and list of related documents necessary for conducting the ARLE.

5.3 Evaluation Techniques

Of the 87, 43 papers have performed user studies on the system regarding ease of use, satisfaction, immersion, student motivation and performance, among others. The number of students involved in the study varied from 4 [23] up to 419 [38] with a median sample size of 36 students [56]. The proper choice of evaluation method for an ARLE depends on the purpose of the evaluation. In our review, we observed two primary purposes: to show whether or not an ARLE is beneficial to learning, and to measure user experience and discover possible improvements.

5.3.1 *Proving ARLE Benefits*

Researchers need to prove the benefits of using their ARLE. Thus, they compare either the performance or the motivation of students when using an ARLE (the experimental treatment) and when using a more traditional medium of instruction (the control). To measure student performance, the students take a test to measure their mastery of the content. Scores of students belonging to the experiment group and control group are then compared to see any differences in learning. Such comparison between ARLE users and non-users are summarized in Table 1. The most critical consideration in this kind of evaluation is the execution of a control group. As much as possible, the researcher must provide the best control possible. For example, to evaluate a location-based AR game, O'Shea et al. [76] designed a board game version of the AR game for students to use in a control scenario.

Aside from possibly improving student performance, ARLEs can be used to increase the motivation of students in educational settings. Abstract constructs such as motivation can be measured by expertly designed questionnaires such as [50] and [2]. In [50], motivational design process is modelled to have four steps. First is to gain the attention of student. Then, guarantee that content is relevant to the student. Next, learners should build confidence by feeling in control and expecting to succeed. Lastly, the reflection of the students on their performance will determine their degree of satisfaction. Whereas [31] focused on designing motivational learning experiences, [40] focused on motivation towards self-learning. In [40], the researchers used a part of the Intrinsic Motivation Inventory (IMI) to analyse four subscales: enjoyment, competence, usefulness, and tension. The IMI had been previously applied to successfully measure subjective experiences related to a performed activity.

5.3.2 Discovering Usability Issues

Researchers also evaluate their ARLEs to measure some aspect of user experience and discover possible improvements to the current prototype. In this evaluation, user study participants are observed while they use the ARLE, and asked questions in the form of an interview or questionnaires after using the ARLE. Survey questionnaires are the most commonly used evaluation tool in the current literature. Questionnaires are designed to measure an abstract construct such as the user's feelings of satisfaction, enjoyment or immersion while using the system. After researchers decide on a construct to observe, they either use existing questionnaires, or create their own questionnaire.

Expertly designed questionnaires have been tested for *validity* and *reliability*, therefore, they give a better measure of the construct of interest. However, crafting a questionnaire specific to a prototype is sufficient to discover possible improvements in that prototype. Currently, there is a need for expertly designed questionnaires to accurately measure ARLE-relevant constructs (e.g. immersiveness). Moreover, an expertly designed usability questionnaire is needed to systematically improve ARLEs under iterative prototyping. Table 5 shows the list of ARLEs that used questionnaires, their corresponding metric or construct evaluated, and the tool that they used.

Some researchers, [101] and [48], have adapted ISONORM, a general software usability questionnaire. Using this questionnaire, they were able to observe aspects of interface design such as conformity with user expectations, controllability, error tolerance, self-descriptiveness, suitability for learning, and suitability for the task.

Among the most observed construct are ease of use, usefulness and intention to use. In the current literature, researchers usually ask directly if a system is easy to use, if the user thinks it is useful, and if they would use the same system for other subject matter. Therefore, most of the available literature measure perceived ease of use and perceived usefulness. However, it is possible to measure ease of use such as counting errors when using the interface and time on a certain task.

5.3.3 Other Evaluation Methods

Other evaluation methods also have their own advantages depending on the context of evaluation.

1. *Interviews* are useful for learning about qualitative data that cannot be captured by written responses to questionnaires. For example, interviews were useful in learning about technology acceptance [101], [28]; possible advantages of ARLE than the current practice of a teacher [51], [26]; and learners' opinion about technology including perceived ease of use, perceived usefulness, intention to use, etc. There are also cases in evaluating ARLEs that interviews would be preferred compared to questionnaires. In cases wherein the respondents are young children or persons with disabilities [110], it is better to conduct interviews in order to communicate effectively what is being asked.
2. *Observing and coding overt behaviors* have been adopted by several papers to see how their target user would interact with an ARLE prototype. Observation is done to reveal possible improvements for better performance and satisfaction of the user. Behaviors can be divided into two: verbal and non-verbal. Verbal behaviors can be specific keywords, expressions, questions or statements a learner says while using the ARLE. Aside from verbal behaviors, nonverbal behaviors can also be revealing of a participant's experience of an ARLE. These include facial expressions (frowning, smiling, surprise, etc.) or body language (fidgeting, leaning close to ARLE, scratching the head, etc.) [105].
3. *Expert review* was used by Margetis et al. [62] to evaluate touch-based interactions with ARLE based on the book metaphor. They employed 4 usability and interaction design experts to perform heuristic evaluation with questionnaires based on the work of Nielsen and Mack [72]. The main goal of the expert review is to identify potential usability problems, and check conformity against five dimensions of usability: effective, efficient, engaging, error tolerant, and ease of learning [83].

TABLE 5
Summary of Preliminary Studies Using Survey Questionnaires

Ref.	Metrics or Constructs	Tools
[31]	attention, confidence, relevance, satisfaction	Instructional Materials Motivation Survey [50]
[39]	enjoyment, competence, usefulness, tension	Intrinsic Motivation Inventory [2]
[86]	challenge, collaborativeness, competition, ease of use, movement, rewards, situated learning	Constructivist Multimedia Learning Environment Survey [61], Preferences for Internet Learning
[56]	collaborativeness, interest, perceived skill development	Learning Effectiveness [5]
[80]	use of computer, use of video game, science process	Self-Efficacy in Technology and Science Short Form [6]
[21]	attitude to e-learning, e-learning experience	Technology Acceptance Model [29]
[98]	ease of use, effectiveness, learnability	Crafted their own questionnaire
[63]	attractiveness, ease of use, usefulness	Crafted their own questionnaire
[46]	ease of use, enjoyment, perceived skill development	Crafted their own questionnaire
[47]	ease of use, enjoyment, usefulness	Crafted their own questionnaire
[102]	enjoyment, perceived presence	Crafted their own questionnaire
[101]	controllability, ease of use, learnability, self-decriptiveness	ISONORM Usability Questionnaire [81]
[7]	wearability	Crafted their own questionnaire
[45]	ease of use, engagement, perceived presence, usefulness	Crafted their own questionnaire
[60]	ease of use, intention to use, usefulness	Crafted their own questionnaire
[59]	ease of use, usefulness	Crafted their own questionnaire
[99]	attitude, ease of use, interest	Crafted their own questionnaire
[8]	ease of use, intention to use, learnability, perceived correctness and responsiveness of system	Crafted their own questionnaire
[93]	ease of use, intention to use, perceived correctness and responsiveness of system	Crafted their own questionnaire
[54]	ease of use	Crafted their own questionnaire
[28]	ease of use, expectations of AR, perceived affordances, usefulness	Crafted their own questionnaire
[33]	ease of use, perceived efficiency, usefulness, preferred subjects to use ARLE	Crafted their own questionnaire
[108]	comfort, enjoyment, intention to use, interest, perceived skill development, usefulness	Crafted their own questionnaire
[48]	conformity with user expectations, controllability, error tolerance, self-descriptiveness, suitability for learning, suitability for the task	ISONORM Usability Questionnaire [81]

6 Applying Theory to ARLE

The design of ARLEs should take advantage of the affordances of AR as enumerated in Section 4.1. These affordances of ARLEs to learning are supported by theories of cognition and learning. These theories help explain how and why ARLEs can be beneficial to learning. Furthermore, insights from these theory can be used to improve the design of ARLEs.

6.1 Hypotheses Based on Cognition

Researchers of human-computer interaction apply psychological theory and methods in understanding human behavior. Among the many contributions of the field of psychology, we have relied heavily on the current understanding of the human memory in designing better interfaces. Based on theory, we hypothesize how ARLEs can be beneficial to learning.

Cognition theories suggest that the human memory is comprised of two related structures: short-term working memory (STM) and long-term memory (LTM). The STM stores information temporarily, whereas, the LTM maintains information more permanently. The STM acts as a *limited working memory* where information is temporarily activated so that a person can operate cognitive processes. These pieces of information are either perceived from the environment or retrieved from the LTM [44]. The LTM contains the knowledge in inactive state. It organizes information into structures that facilitate the retrieval of information. Figure 5 illustrates the flow of information through the human memory system.

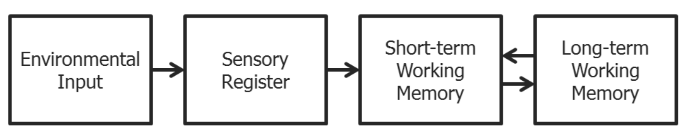

Fig. 5. Theory of memory as proposed by Atkinson and Shiffrin emphasizing the interaction of sensory stores, STM and LTM. Input from the environment is held for a few hundred milliseconds in the sensory register. The STM acts as a working memory holding data from both sensory registers and long-term memory, and performing cognitive processes [85].

People store much more information than what is presented to them. Aside from the concepts to be remembered, we also generate associations that help us make sense of, and thus remember, information. Elaboration is the creation of such additional associations. There are two kinds of elaboration: imprecise elaboration and precise elaboration.

Imprecise elaboration is the creation of additional associations unrelated to remembered information. Whereas, precise elaboration is the creation of additional material closely related to remembered material [85]. When learning, students sometimes take advantage of elaborative rehearsal: a memory technique that involves thinking about the meaning of the term to be remembered. Aside from this semantic processing, the use of visual imagery and haptic information can also be a powerful form of elaboration of knowledge.

Based on this understanding of human memory, we hypothesize that there are three ways ARLEs help students learn better:

1. *Real world annotation* improves perception. It juxtaposes real objects, and virtual text and other symbols. This reduces cognitive load in the limited working memory so that a bigger fraction of the STM can be used for operating cognitive processes(e.g. storing in the LTM).
2. *Contextual visualization* improves elaboration. ARLEs provide more meaningful cues found in the real environment that help a student construct a more elaborate network of knowledge.
3. *Vision-haptic visualization* improves elaboration based on embodied imaging. It presents visual information in two modalities: sense of sight and sense of touch.

Real world annotation, contextual visualization, and vision-haptic visualization are discussed under Sections 6.2, 6.3 and 6.4, respectively.

6.2 Real World Annotation

The most basic application of AR is the annotation of real world objects and environments. Merriam-Webster defines annotation as ”a note added by way of comment or explanation.” The data being annotated would be text meant to explain a concept. Many AR applications, including ARLEs, use text as the virtual information being overlaid to the real environment. However, annotation with AR is not limited to text. It could also involve other symbols and icons. This includes, but is not limited to, arrows and basic shapes such as circles and lines used to highlight or direct a user’s attention.

AR annotation is the juxtaposition of real world objects or environments with virtual text or virtual symbols that help explain a concept to a user. Some researchers also use the term annotation to refer to information-tagging such that a physical object becomes a link to access images, videos and webpages. In this paper, information-tagging is not considered as AR annotation.

6.2.1 Real Object-centered

ARLEs that use AR annotation are a class of ARLEs wherein a system of objects become the central point of learning. The system of objects is augmented with text information or other symbols with the purpose of providing a learning experience. By definition, the virtual information is the text or symbol, and the real environment is the system of objects. To be consistent to the definition of AR, AR annotation requires tracking the physical objects such that the text information appears as labels that follow the real object.

6.2.2 Multimedia Learning Theory

The benefits of AR annotation can be directly explained using Multimedia Learning Theory [67]. In this theory, multimedia refers to words (written or spoken) and pictures. Multimedia learning theory has three assumptions namely dual channels, limited capacity, and active processing. The first assumption is that there are two separate channels for visual information and auditory information. The second assumption is that both these channels can only accommodate a limited amount of information at a given time. Lastly, the third assumption is that humans are active learners. Incoming information from the channels are processed by organizing them into coherent mental representations, and integrated to previously acquired knowledge. Using these three assumptions, Mayer has derived and empirically proven design principles in authoring multimedia learning materials. Of these principles, the following are directly related to AR annotation applications namely: *Multimedia Principle, Spatial Contiguity Principle, and Temporal Contiguity Principle*.

Multimedia learning theory can be extended to AR annotation by doing two substitutions:

1. The system of real objects replaces the picture.
2. The virtual texts and symbols replaces the words.

From this theory, it can be argued that learning with AR annotated objects is better than learning about the same object with other reference material such as a manual or a separate online source. For example, in learning how to play a guitar, it will be better to learn about the finger positions highlighted onto the guitar, than referring to a sheet summarizing the finger positions for each chord. By the definition of AR annotation, three empirically-proven principles namely Multimedia Principle, Temporal Contiguity Principle, and Spatial Contiguity Principle guarantee that learning with AR annotated physical objects will lead to better learning performance than a more traditional way of learning. The extensions of these principles to AR annotation are shown in the Table 6.

6.2.3 Memorization

The principles of multimedia learning theory were tested both on printed materials and computer-assisted instructions. It has not yet been tested for AR annotation applications for learning. However, Fujimoto, et al. [35] has demonstrated how the annotative abilities of AR can

TABLE 6
Multimedia Learning Principles Supporting the Effectiveness of AR Annotated Objects [67]

Principle	Extension to AR Annotation
Multimedia and Time Contiguity	People learn better from annotated virtual words onto physical objects than from separate multimedia (e.g. illustrated manual) and physical objects.
Spatial Contiguity	People learn better when corresponding virtual words and physical objects are presented near rather than far from each other on the screen.

ease memorization tasks. In their study, the memorization abilities of users were tested for when they memorized symbols by annotating information near the target object (Display 1), against displaying the information on a random place while connected by a line (Display 2), and on the same place, say at the top left of the display (Display 3) as shown in Figure 6.

Fig. 6. Three display methods. On the left is AR Annotation wherein a label is placed near the relevant part of the map. The middle and right are control scenarios wherein a label is displayed randomly on the map with a connecting line, and a label is displayed consistently at the top left of the HMD screen without a connecting line, respectively [35].

Fujimoto, et al. conducted two types of memory tests: identification and association. In these tests, each of the participants are shown 10 symbols one at a time. The identification test asks the participants to identify the 10 symbols they just saw from 25 symbols. Whereas, the association test asks the participants to identify where in the map they saw the image. In both tests, Fujimoto et al. measured the accuracy of answers, as well as the time it took for the participant to answer.

Results show that annotating the information on top of an object (Display 1) allowed the users to memorize the labels significantly better than when displaying the information on random places (Display 2), or on the same place on a display (Display 3). In the identification tests, participants were able to able to achieve an accuracy of 99% with Display 1, 95% with Display 2 and 96% with Display 3. The bigger difference is in the answer time wherein users of Display 1 answered in a shorter time of 45 seconds, compared to 53 seconds and 52 seconds for Displays 2 and 3, respectively.

In the association tests, participants were 87% accurate with Display 1. Whereas, they are only 70% and 75% accurate with Displays 2 and 3, respectively. Furthermore, participants who used Display 1 finished the test in 96 seconds, compared to 112 seconds and 99 seconds for Displays 2 and 3, respectively.

All of these tests were proved to be statistically significant in the paper of Fujimoto et al. Annotating virtual information near an object makes perception easier, and can be use to better present information in educational settings.

6.2.4 Examples

One example of AR annotation is the work of Simeone and Iaconesi [96]. In their work, they trained their system to recognize 3D parts of a model airplane (Figure 7.a) so that they can display relevant information for each 3D part. Their system makes use of a personal computer equipped with a webcam. The virtual information can be viewed on the computer monitor together with the real environment including the airplane model and the user.

The authors mentioned two use cases. First, instructions on how to assemble the several pieces into an airplane can be annotated on to the 3D part. When a user picks up a piece and puts it near the webcam, an instruction relevant to that part is displayed at the bottom of the screen. Instead of the student going back and forth from a manual to the actual objects, the airplane model pieces can be augmented with the manual instructions.

Second, the airplane model can be layered with several kinds of information that the students can access by focusing on specific parts of the plane. The information was taken from various online sources. This prototype is limited in its annotating capabilities because the system does not have a tracking feature. With a tracking feature, the annotated information can be able to follow the real object wherever it is on the screen. However, for the purposes of a prototype, this work is a good approximation of how AR toys can be used in the near future.

Instead of text information, other symbols and shapes can be used to annotate objects. In physics education, magnetic field lines (Figure 1) [66] and directions of forces acting on an object (Figure 6.c) [99] have been annotated to real objects like magnets and carts, respectively. With this feature, students can visualize abstract phenomena like magnetic field and force.

Another set of compelling examples can be found in ARLEs with the goal of teaching how to play musical instruments. AR applications have been developed to teach people how to play the guitar [70], drums [108] and piano [39]. In [70], a desktop system was used to render a virtual hand on top of a real guitar. The student can then position his hands correctly on a guitar. Instead of the student translating a chord sheet indicating which strings to press at which fret, this information is already annotated on the guitar itself.

In [108], a projector-based AR annotation was used to indicate on a drumset which drums to hit by projecting

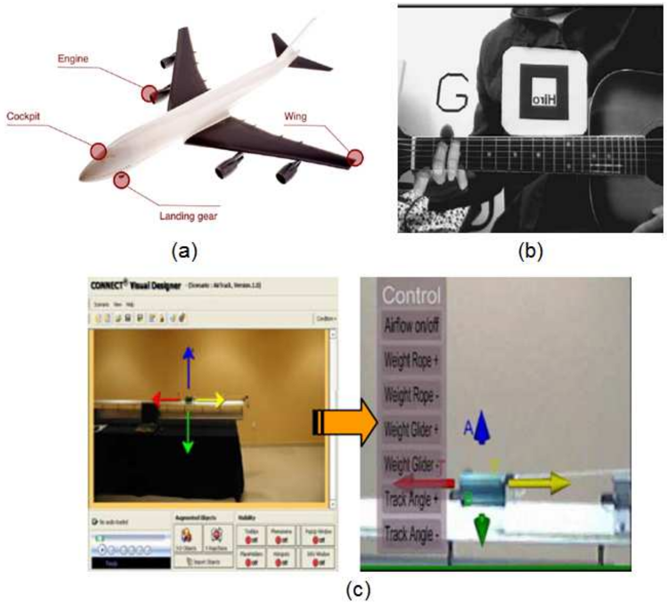

Fig. 7. Some ARLEs demonstrating annotation. (a) shows the parts of the airplane that can be recognized and annotated with words in the work of Simeone and Iaconesi [96]. (b) shows the virtual hands and letter annotated on a real guitar [70]. (c) shows a cart augmented with arrows representing forces acting on it [99].

circles on the top of the appropriate drum. Instead of a teacher demonstrating to the student and pointing which drums to hit, this information can be augmented directly onto the drum set.

Lastly, in [39], a desktop AR annotation system is use to demonstrate finger positions on a piano. Instead of a piano teacher demonstrating the proper finger positions, this information can be augmented on a keyboard. These systems do not intend to replace formal training with music teachers. However, these systems are very useful for self-studying outside of the formal class, and for music teachers to create learning materials for their students. The other examples of ARLEs using annotation are listed in Table 7.

TABLE 7
Examples of AR Annotation

Ref.	Real Objects	Virtual Annotations
[31]	Printed replicas of Renaissance art	Text details relevant to art
[22]	Library	Verbal hints from a virtual character about the structure of the library
[66]	Magnets	Magnetic field lines
[11]	University campus	Signages
[39]	Piano	Highlights of correct finger position of a musical note
[40]	Go Boardgame	Boardgame pieces (stones) added in strategic patterns
[75]	Playing cards	Scoreboard and strategic use of cards on hand
[97]	Cultural Artefact	Text details relevant to anthropology
[108]	Drumset	Highlights of sequence for hitting drums
[96]	Airplane model	Description and instruction relevant to the airplane part
[70]	Guitar	Highlights the finger position of chord
[99]	Cart and other objects	Forces acting on the object as it moves
[24]	Ball	Arrows representing instantaneous velocity, acceleration, and centripetal force

6.3 Contextual Visualization

The ARLE developers have designed ARLEs such that it makes use of contexts that students can relate to. The current literature on ARLEs suggests that AR inherently offers a *contextual visualization* of virtual information. Contextual visualization refers to the presentation of virtual information in the rich context of a real environment. The virtual information is always presented within a context, that is, a real environment. This context is filled with cues that help students construct their knowledge [89].

6.3.1 Experiential Learning Theory

Multimedia learning theory provides a learning theory of how real world annotation by AR can help students learn better based on human cognition and related processes in the brain. This theory is complemented by Experiential Learning Theory which views entire experiences as the source of learning. Experiential learning theory is different from cognitive theories of learning that give primary emphasis on acquisition, manipulation, and memorization of symbols.

Experiential learning theory explains that people learn by creating meaning from their personal experiences. It describes four stages in the learning cycle as shown in Figure 8. Learning starts with having a concrete experience, which becomes the basis of observation and reflection. From our observations, we formulate theories, which we test for implications in new situations. Results of this testing stage provide new concrete experiences [53].

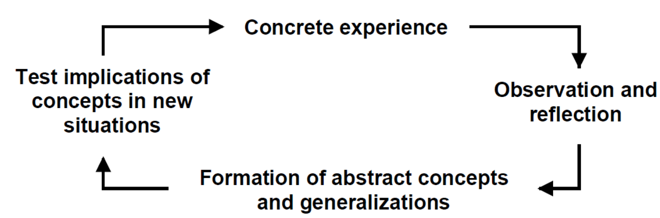

Fig. 8. Lewinian Experiential Learning Model

6.3.2 Contextual Learning

Contextual learning is a curriculum design philosophy that applies experiential learning theory. It recognizes the importance of context in learning experiences, that is, learning only occurs when students process new information with their personal experiences [3]. In the classroom, contextual learning is observed when using five strategies [27]:

1. *Relating* - to link a new concept to something students are familiar with,
2. *Experiencing* - to let students explore, discover or invent so that they can learn by doing,
3. *Applying* - to give students an opportunity to use the concepts in realistic and relevant exercises,
4. *Cooperating* - to give the students a chance to share, respond and communicate with other learners,
5. *Transferring* - to give the students the chance to use their new knowledge in a new context or novel situation.

Similarly, contextual visualization using ARLEs can be used as a strategy to link virtual information to an object or an environment that a student is familiar with to provide more effective learning experiences.

6.3.3 Examples

In [58], students learn the English language around a campus using a handheld ARLE prototype. The lesson included vocabulary and sentence patterns used in the classroom, gallery, library, gym, laboratory, cafeteria, and health clinic. In this instructional design, students are already familiar with the school campus and the language used in the different types of places on campus. By presenting information in these real environments, the virtual information is automatically related to what the students are familiar with. This makes it easier for them to relate it with their previous experiences.

Moreover, some of these ARLEs offer some form of experience that would otherwise be difficult to observe in real life. An example would be [104] which allows the visualization of virtual butterflies in the school garden. In the normal setting, it is difficult to observe a butterfly from egg to a full butterfly. In some cases when students live in a very urbanized area, butterflies may not even be readily observable. Moreover, the method in [104] is a better visualization because the students are already familiar with the school garden. It makes it easier for them to learn that such garden ecosystems may include butterflies that undergo metamorphosis.

The last example is [22] which aims to teach students library skills inside a library setting. This gives the students the chance to try looking for books and finding information for themselves. The library was layered with additional information that both directs the students and scaffolds them into being able to find information they need. The other examples are summarized in Table 8.

TABLE 8
Examples of Contextual Visualization

Ref.	Content	Context
[58]	English language	School campus
[104]	Butterfly life cycle	School garden
[22]	Library skills	Library
[86]	Animal and plant life	Local park
[65]	Animals	Zoo
[49]	Architectural history	Building
[78]	Finding offices of institutions designed for deaf students	Street in front of school
[52]	Location-based story game	Local neighborhood
[77]	Asian art	Museum
[7]	Airflow, Magnetism, Force	Science Centre
[64]	Location-based game for learning scientific language	Local neighborhood
[71]	Historical events	Original place where event happened

6.4 Vision-haptic Visualization

Recently, researchers have argued the benefits of tangible interfaces for learning based on the additional physical actions they afford and the possible face-to-face collaborative activities they support. Moreover, the coupling of tangible user interfaces with AR enables a close mapping between tangible input (manipulations of a physical object) and digital output (on-screen display) [92].

Vision-haptic visualization is the integration of both the sense of sight and the sense of touch in perceiving virtual information. This is mainly observed when changing the viewpoint of a user such that in ARLEs: The user can pick up an object, and inspect the corresponding virtual content from different angles by rotating the object, and moving the object nearer or farther from them. Moreover, the users can move around an object to see the other parts of the corresponding virtual object.

6.4.1 Animate Vision Theory

Shelton and Hedley [95] argue that embodied interactions are more natural visualizations of virtual information based on the Animate Vision Theory [10]. This theory links visual perception to acting and moving in the physical world. Visualizations in learning experiences should take advantage of visual stimuli and motor responses. Straight-forward examples are providing feedback using virtual reality (VR) for teaching a person how to dance [109]. In a test involving 8 participants, Chan et al. have demonstrated a VR-based dance training system with a very large effect size of 1.66 [17].

Aside from VR, AR is applicable for this purpose because it allows users to use their hands and entire bodies to change the perspective of visualization.

In an empirical experiment involving 100 participants, AR users have been shown to accurately finish spatial problem-solving tasks in 1.57 seconds (22%) faster than desktop users during the first use. However, this margin decreased to 0.3 seconds (5%) after the desktop users have sufficient practice using the desktop system [95].

The work of El Sayed et al. [33] provides a straightforward illustration of vision-haptic visualization. They proposed a system wherein each student is given AR marker cards. Depending on the current lesson, 3D virtual models of related objects can be assigned to the markers and then viewed by the students on top of the cards. Instead of illustrating the learning object as an image projected on a screen or printed on a book, the students are presented with a 3D virtual object. (They recommend using the mirror metaphor since many schools are already equipped with desktop computers.) Based on the work of Shelton and Hedley, this interaction with virtual information is superior because of two reasons:

1. The interaction of students with the virtual object is not mediated by a mouse or keyboard. They can move around the virtual object or change its orientation using their bare hands. This kind of interaction is closer to what we normally do when we study an object. We pick it up, sometimes we tilt our head to see the sides, we hold it closer to us to make it bigger, etc. In [32], the students can move around a virtual geometric shape. The user's body becomes the way to interact with information against the more conventional mouse and keyboard.
2. This interaction is better for some applications compared to virtual reality which presents the user with both virtual environment and virtual objects. In virtual reality, we try hard to provide the illusion of transporting the user to a different world. In some cases, it is better to keep the users' awareness of themselves and their immediate surroundings. When using AR, the students' awareness of their bodies and their real environment remains intact. For example, the work of [14] allows the students to visualize the muscles and organs inside their bodies. If they move their shoulder or arms, they can see the body organs at different angles. This ARLE is able to provide a more compelling experience by contextualizing the virtual information to the learner's body.

6.4.2 Examples

Several ARLEs (Table 9) provide embodied interactions when visualizing virtual data. For example, [63] displays a virtual object on a notebook. Then, students can rotate and tilt the notebook to see other parts of the virtual object. Another example would be [66] wherein students move around magnets (painted wooden blocks) using their hands to see how the virtual magnetic fields change. In [102], users can tour a room converted into a virtual museum wherein the artefacts on display are virtual. Similar to how users would behave in an actual museum, they can inspect a virtual object by peering over different angles with respect to a fixed virtual object.

TABLE 9
Examples of Vision-haptic Visualization

Ref.	Content	Embodied Interaction
[14]	Human anatomy	Users can move around to see his internal organs
[63]	Spatial ability training	Users can rotate a virtual model displayed on his notebook
[66]	Magnetic field concepts	Users can move around magnets and see how the magnetic field changes.
[82]	Chinese characters	Users can hold 3D virtual objects representing the characters
[56]	Elastic collision	Users can view two colliding balls at different perspectives.
[33]	3D objects related to the lesson	Users are presented with 3D models on cards they can manipulate by hand.
[106]	Children's story	Users are presented with a 3D pop-up book.
[58]	Solar system	Users are presented with heavenly bodies on a book.
[79]	Digestive and circulatory systems	Users are presented with 3D virtual models of internal organs associated with an AR marker.
[102]	Art and cultural objects	Users can tour an AR museum.
[23]	Amino acids	Users are presented with 3D virtual models of amino acids.
[32]	Geometry and spatial ability	Users can move around a virtual geometrical shape.
[34]	Electronegativity and dipole moment	Users are presented with 3D virtual models of molecules.
[94]	Solar system	Users are allowed to change the position of the Earth with respect to the sun and observe the effect on the Earth.

7 Conclusion

Augmented Reality (AR) has unique affordances that can affect the learning experience. Developments in AR technology have enabled researchers to develop and to evaluate Augmented Reality Learning Experiences (ARLEs). These developments encompass hardware, software and the authoring of content. Currently, ARLEs have a mean effect size of 0.56 to student performance with wide variability due to the many possible ways to use AR, as well as, differences in experimental design.

In the course of the development of ARLEs, researchers must test their prototypes for benefits in the learning process, and for usability. Such tests must use sensible control groups, report an effect size, and use expertly designed tools such as questionnaires. ARLEs have been evaluated through student performance tests, survey questionnaires, interviews, observations of user behavior, and expert reviews. Currently, there is a need for valid and reliable questionnaires to measure constructs related to ARLEs to iteratively improve ARLE design.

A review of existing ARLE prototypes led us to the conclusion that there are three inherent affordances of AR to educational settings namely: real world annotation, contextual visualization, and vision-haptic visualization. Furthermore, researchers have used design strategies such as enabling exploration, promoting collaboration, and ensuring immersion to create compelling learning experiences. Depending on the learning objective, these affordances and strategies can be employed to create successful ARLEs.

These three affordances are supported by existing theories namely multimedia learning theory, experiential learning theory and animate vision theory. Essentially, AR affords interactions with information that may help us perceive and remember information based on multimedia learning theory and animate vision theory. Real world annotation may reduce cognitive load significantly, and vision-haptic visualization allows embodied interactions enabling more natural ways of acquiring information. These highly cognitive approaches to understanding AR technology in educational settings are complemented by experiential learning theory and contextual learning which treats the whole experience of the students as the source of learning. Adapting AR technology changes the learning experience and may afford new compelling experiences that lead to better learning.

Researchers, teachers and students are already collaborating towards a more participatory design of ARLEs. In the future, we believe ARLEs will be created by more interdisciplinary groups and will be grounded in theory. Future work in the area of ARLE would be empirically proving (or disproving) the principles of multimedia learning theory for AR annotation, ARLEs and AR in general. Basic research should also be done in exploring contextual visualization and vision-haptic visualization. This includes, but is not limited to experiments measuring learning with varying degrees of contextual cues, and when using varied, embodied interactions.

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