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Augmented Reality in Education: A Meta-Review and Cross-Media Analysis

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Abstract

Augmented reality (AR) is an educational medium increasingly accessible to young users such as elementary-school and high-school students. Although previous research has shown that AR systems have the potential to improve student learning, the educational community remains unclear regarding the educational usefulness of AR, and regarding contexts in which this technology is more effective than other educational mediums. This paper addresses these topics by analyzing 26 publications that have previously compared student learning in AR vs. non-AR applications. It identifies a list of positive and negative impacts of AR experiences on student learning, and highlights factors that are potentially underlying these effects. This set of factors is argued to cause differences in educational effectiveness between AR and other media. Furthermore, based on the analysis, the paper presents a heuristic questionnaire generated for judging the educational potential of AR experiences.

Keywords: Augmented Reality, Education, Comparative Studies, Children, Human Factors.

Introduction

Educational content can be experienced through a wide variety of media, ranging from non-interactive books, to highly-interactive digital experiences that fully engage the user's senses. This paper is concerned specifically with analyzing the emerging medium of augmented reality. A relatively high amount of research studies have investigated the potential impact of augmented reality to benefit student learning. These diverse research programs can provide useful information for educators and technology designers interested in enriching young students' minds through novel technologies. Currently, however, there is no comprehensive understanding of the educational impact of the evolving medium of augmented reality. Having an integrated analysis of the various empirical research studies can provide a theoretical basis, as well as practical guidance, to current and future educational initiatives interested in leveraging the educational benefits of augmented reality.

This paper presents a step towards such an integration, and aims to provide a comprehensive understanding of how the medium of augmented reality differs from other educational mediums. It synthesizes a literature review of academic publications that investigate how human learning differs between AR and non-AR experiences. From the analysis of these publications, the paper identifies positive and negative effects that AR experiences can bring to learners. Further, the paper highlights various technological and psychological factors that may account for the observed learning effects, and presents a questionnaire for scoring these factors in existing AR experiences. By integrating these research findings and highlighting the potential underlying factors, this research constructs a model of the factors that may maximize the use of AR for learning.

The paper is structured under five sections. First, it provides an introduction to augmented reality as a medium for educational experiences. Second, it provides an overview of the research methodology. Next, it offers a summary of results from the studied literature, identifying benefits and detriments found when comparing AR to other media. Following, it discusses how the AR medium differs from other media, and provides an analysis of the factors that can specifically benefit learning in AR. Finally, the paper presents a heuristic questionnaire aimed at evaluating the educational effectiveness of AR experiences, and concludes with future work.

Augmented Reality as Educational Medium

Educational content can be experienced through a wide variety of media. Students traditionally learned through interaction with teachers and peers, and through non-interactive media such as textbooks and instructional videos. In the last half century, digital media has increasingly made its way into educational settings, providing students with learning opportunities around interactive simulations and educational games. Digital learning experiences have typically been accessible in classrooms equipped with desktop computers and interactive whiteboards, and more recently learning experiences are increasingly accessible through students' portable devices such as smartphones and tablets. Furthermore, the manner of interaction with learning experiences is changing: students do not only use keyboards and mice to interact with on-screen content (as was possible with traditional desktop software), but now students can use their whole body to interact with educational content that appears to exist in the physical world (as possible through augmented reality technology).

This paper is primarily concerned with analyzing the educational potential of augmented reality technology, as compared to other educational mediums. Augmented reality brings virtual information into a user's physical environment, and allows the user to user their whole body to interact with the virtual content [1, 2]. There are many potential benefits which augmented reality technology can bring to children's lives, such as enhanced entertainment through whole-body interaction [3, 4], advancing education through in-situ interactive visualizations [5, 6], and improving rehabilitation and skill development through physical manipulation [7, 8].

Augmented reality experiences can take a variety of forms. Smartphone-based AR applications allow users to travel through their environment while looking at their augmented

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world through a mobile device [9], but the mobile device limits the user's ability to physically interact with the augmented space. Webcam-based AR applications make use of a computer camera to capture a physical space and display an augmentation on a screen, such as a desktop monitor or well projector, allowing the user to use their hands to easily manipulate the augmented content. Some webcam AR applications are similar to Kinect and Wii platforms, in that they make use of a large space such as a classroom, allowing the user to user their whole body to control a virtual experience and observe effects on a separate screen; however, the difference between these and AR experiences is that in the AR experience, virtual content is placed in the physical space surrounding the user [10]. Finally, head-mounted-display (HMD) AR applications require users to wear specialized goggles, which contain an internal display and attached video camera; these permit the user to have a personal perspective on the augmented space, and to be able to use their hands to easily manipulate the AR experience [11].

Meta-Review Methodology and Limitations

This paper surveys multiple publications that have compared augmented-reality to non-augmented-reality learning. Although previous research has theoretically argued for the benefits of using augmented reality in education [12, 4], the current paper offers a meta review of existing empirical studies comparing AR to non-AR systems for learning, and discusses learning affordances of AR in comparison to different media. The corpus for the literature review was selected by searching online databases for conference and journal articles discussing comparisons of AR and non-AR applications. During data analysis, one coder read all the articles, and performed open coding on sections relating to evaluation results and discussion. The coding was limited to corpus sentences that related to learning, cognition, or usability. Codes were then clustered into the categories presented below. The articles included in the corpus are all referenced in the current manuscript.

The categories presented below are indications of the educational benefits and pitfalls of AR experiences. However, it is worth stressing that these characteristics may not always be present in all augmented-reality applications. Each AR application is unique, influencing students in specific ways according to its design; thus these categories simply indicate possibilities in which AR experiences may influence student education.

Learning Benefits from Augmented Reality

This section reports the positive impact that augmented reality experiences has been shown to have on learners, as compared to non-AR initiatives.

Increased Content Understanding

A large proportion of the surveyed papers indicate that for certain topics, AR is more effective at teaching students than compared to other media such as books, videos, or PC desktop experiences.

Learning Spatial Structure and Function

In a wide range of the comparative studies, students are successfully taught about spatial domains - such as geometrical shapes, chemical structures, mechanical machinery, astronomy configurations, or spatial configuration of human organs. The studies generally indicate that students learn better when using AR than when using either printed media, or using desktop software.

Lindgren & Moshell [13] compare children's learning of astronomy between two systems: a PC-based application where children interact with a mouse, and a projector-based mixed-reality (MR) application where children interact by walking on a floor surface. Although quantitative significant differences were not found, the qualitative analysis shows differences in the way children conceptualized the content. The MR group appeared to be focused on the dynamics of planet movements, while the PC group seemed more focused on surface details such as the visual look of the planets. The results of this research point to potential cognitive differences in student's experience of AR vs. PC environments.

In a series of studies, Vincenzi and colleagues [14-17] required students to learn the components of an aircraft turbine engine, using AR, video, and textbook conditions. The research shows that under the AR condition, student exhibited better short-term memory and long-term memory (as tested 1 week later).

Hedley [18] compared college students learning geography under AR vs. PC conditions. The research indicates that students in AR condition constructed more detailed mental representations than the PC group.

In Sin & Zaman's research [19], students learned about characteristics of the solar system using either an AR or textbook. Students using the AR system showed greater learning, improving their pre-test scores by 46%, while students using the textbook improved by 17%.

Seo, Kim & Kim [20] tested the effect of AR in a classroom setting, as students 9-12 years old learned about volcanoes. The study compared the effect of teaching with textbooks, teacher-controlled AR, or student-controlled AR. The research shows that students learned significantly better under the AR conditions, but no significant differences were found between the AR groups.

Chen [21] showed that students will have a better understanding of chemical structures when they learn individually using AR vs. using textbooks.

In the domain of human anatomy, Nischelwitzer et al. [22] show that students who use an interactive AR system will learn better than using a traditional textbook. It is worth noting that in this research, the AR system did not only provide interactive 3D visualizations, but also administered test questions.

In a study of medical training, Quarles and colleagues [23] observed students learning about internal functioning of medical machinery. Students who used an AR system (which overlaid machinery diagrams on a real-world machine) were better able to transfer knowledge to a real-life situation, as opposed to the students who learned using a VR system (which showed similar diagrams but without the real-world context).

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Learning Language Associations

Other studies have looked at using AR for teaching symbolic associations, such as teaching the meaning of written words.

Chen et al. [24] describe an AR system for teaching Chinese students the meaning of word pictograms. Children's memory, as well as reading and writing scores, improved more when learning through the AR as compared to learning from a textbook.

In a similar system, Freitas & Campos [25] constructed a system for teaching Grade-2 English students the meanings of animal and vehicle words. In a class setting, a teacher instructed students using either the AR system or a traditional textbook. Students who were low- and average-achievers learned more from exposure to AR approach; however, high-achiever students learned better when exposed to the traditional approach.

Long-Term Memory Retention

Research indicates that content learned through AR experiences is memorized more strongly than through non-AR experiences.

As mentioned above, studies by Vincenzi et al [17] and Valimont et al [16] show that when students learn about aircraft turbines, content learned through an AR experience is significantly more likely to be recalled one week later, than compared to content learned through paper or video media.

Further, Macchiarella et al [14, 15] show that, for students who learned about turbines using the AR experience, the long-term memory did not significantly degrade after one week. Students who learned from other media, such as books or videos, showed significant decreases in memory recall, yet interestingly, at the time of training no significant differences were found in short-term memory between the groups.

Improved Physical Task Performance

Many studies have showed that when users must train or perform a physical task, AR is more effective than using traditional media. Through an AR experience, maintenance tasks are performed with higher accuracy, and students are better able to transfer their learning to operating physical machinery.

Henderson & Feiner [26, 27] explore the use of AR in guiding repair & maintenance activities on military tanks. Compared to the use of a non-AR system, users of the AR system showed significantly faster speed in locating important items, and showed significantly less head movements. However, overall task performance was not significantly different between the conditions.

Pathomaree & Charoenseang [28] observed users assembling 2D and 3D puzzles, while either using an instructional AR webcam-based system, or no system at all. Users in the AR conditions showed faster task completion time, and less extra steps than compared to non-AR conditions.

Tang and colleagues [29, 30] observed college-age students performing a similar object-assembly task. Users were split into four groups: paper-based 3D diagram, monitor-based 3D diagram, head mounted display (HMD) 3D diagram, and HMD AR display. Users in the AR condition had the fastest task completion times and lowest amount of errors (this result was significantly different than the paper-based group, but not significantly different compared to the other groups). Users in the AR condition also had significantly lower cognitive load compared to the other conditions, measured through NASA TLX.

Improved Collaboration

AR experiences have been shown to cause improvements in group collaboration, as indicated by several papers surveyed.

Morrison and colleagues [31] observed students navigating a neighborhood using either an AR map (ie: a mobile device displaying AR content on a paper map), or a digital map (ie: a mobile device showing a digital map based on GPS location). In the AR group, the student collaboration was determined to be more effective - using the AR application created a shared space where team members could collaborate and create shared meanings, as opposed to the more individual experience of a student using a GPS mapping application.

In a classroom setting, Freitas & Campos [25] observed that class collaboration increased when students used a shared display for observing AR experiences, as opposed to non-technological instruction.

While studying how people collaborate in solving spatial problems under head-mounted AR vs. projector-based AR vs. non-AR conditions, Billinghurst and colleagues [32] find that the use of gestures is similar between AR and face-to-face condition, yet different than the projector-based condition (where significantly less deictic gestures occurred). This effect likely occurs because in the similar conditions, people are facing each other while collaborating. However, it is worth noting that task performance in the AR condition was slower than in the other conditions, and that subjects reported the face-to-face condition to be most conducive to collaboration. The subjects reported several usability issues, and these may account for the detriments in collaboration.

Increased Student Motivation

The users' high enthusiasm to engage with AR experiences is noted in multiple papers, where users report feeling higher satisfaction, having more fun, and being more willing to repeat the AR experience. Interestingly, user motivation remains significantly higher for the AR systems (vs the non-AR alternative) even when the AR experience is deemed more difficult to use than the non-AR alternative. From the literature reviewed, the following papers are noteworthy:

Kaufmann [33] reports that students learning 3D structures using AR vs. a PC CAD program, rated AR as significantly more satisfying than the PC program, even though usability of the AR program was rated lower than the PC alternative.

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Juan et al [34] found that children found a head-mounted AR game to be significantly harder to use, than compared to a non-AR version of the game, yet children found the AR version significantly more fun, and they were more willing to play again.

In studying an alternate-reality game, Liu et al [35] find that the GPS-based game increased student motivation, creativity and exploration, more than its paper-based counterpart.

Learning Detriments from Augmented Reality

This section reports the negative consequences observed when using AR vs. non-AR systems.

Attention Tunneling

In a portion of papers, students reportedly experienced higher attentional demands from AR system. This resulted in the student ignoring important parts of the experience, or feeling unable to properly perform team tasks.

Tang et al [8] observe that participants performing object-assembly tasks under AR condition were more likely to ignore previous errors, than compared to participants in a paper-based condition. The authors note that the “attention tunneling” effect may be hazardous in some situations, and is caused due to the system cuing users’ attention.

In the study by Morrison et al [31], students reported that they had to pay more attention when using the AR system with a paper map, than compared to a purely digital GPS-based map. Other studies of GPS-based AR systems report that users may be so engrossed in the experience that they engage in risky activities, such as walking into traffic [36].

Billinghurst et al [32] asked people to collaborate in head-mounted AR and non-AR configurations. Some participants reported that the head-mounted AR system created “tunnel vision”, likely due to the limited field of view.

Usability Difficulties

In several studies, users rate AR systems as more difficult to use than the physical or desktop-based alternatives. As reported earlier, interestingly, some of these studies also find that users like the AR systems more than the alternatives.

The map study by Morrison et al [31] indicates that students perceived the AR-based map as being more difficult to use than the non-AR counterpart.

In the studies by Kaufmann [33], usability issues are reported relating to head-mounted AR systems. Students rate the AR system as less usable than its PC counterpart, yet students were enthusiastic about prolonged engagement with the system.

The study by Billinghurst et al [32] also indicates that participants reported usability and perceptual issues related to the head-mounted AR system.

In the study by Juan et al [34], children rated the head-mounted AR system as being less easy to use than the non-AR game. However, students rated their willingness to play with the AR system as higher than the non-AR game, and the AR game was significantly rated as being more fun to play than the non-AR game.

Ineffective Classroom Integration

In one paper, the authors show how AR can negatively impact the classroom experience. Kerawalla et al [37] indicate that in the non-AR experience, the students (under the presence of the teacher) were more engaged in exploration and role-play activities around the learning content. On the other hand, during the AR experience the teacher dominated the discussion and limited student engagement with the educational content presented through AR.

Learner Differences

Some studies reported that for some students, AR may not be an effective teaching strategy. In the research by Freitas & Campos [25], the authors report that although low- and average-achiever students showed learning gains through the AR experience, high-achieving students did not receive the same benefits. In fact, the high-achieving students showed more learning gains in a traditional classroom where AR was not used. Potentially, the AR-based educational content was too limited in scope, and did not contain novel information for the high-achieving students. Hornecker & Dunser [38] indicate that students who were low-ability readers did not learn from parts of the AR experience which presented textual content. This is not surprising, but it does reinforce the issue that educational games must be well-tailored to the capabilities of its audience.

What Factors Influence Learning in AR?

Augmented reality applications are complex technological experiences, delivering learning content through a medium different from non-AR experiences. The beneficial learning effects noted above are likely a result of AR experiences exploiting a variety of factors that are not present in non-AR experiences.

Previous work in [12] has analyzed a variety of factors impacting the educational effectiveness of augmented-reality experiences in mathematics classrooms; however, the previous research was specifically focused on comparing AR to non-AR mathematics manipulatives in a classroom context. The present section employs a different perspective, analyzing how AR and non-AR media differ across a wide range of contexts. Educational experiences are decomposed into factors that may foster learning, and these factors are discussed in relation to various media. By understanding the underlying technological and psychological factors which augmented-reality can leverage in educational experiences, designers and educators can make use of the specific affordances of the AR medium in order to construct effective learning experiences.

Table 1 presents a comparison between various media, ranging between books, desktop PCs, smartphones, and head-mounted displays. Different media are compared across factors that provide educational affordances, such as range of representation, ability to align representations, support for interactivity, etc. These factors are then discussed in the upcoming sections.

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Table 1. Cross-media comparison of factors that can influence student learning. Media are rated on how strongly they address each factor, with ratings between: Weak, OK, Strong.

Educational Affordance	**Non-Interactive Media**		**Interactive, Non-AR Media**				**Interactive, AR Media**			
	Books	Video	Desktop PC (non-AR)	Smartphone (non AR)	Interactive Surfaces (whiteboards /tabletops)	Wii / Kinect (non-AR)	Smart phone +GPS -No Camera	Smart phone +GPS +Camera	Webcam Desktop PC /Projector	Head Mounted Display +Camera
MULTIPLE REPRESENTATIONS										
Auditory	*Weak*	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**
Visual Text	**STRONG**	OK	**STRONG**	OK	**STRONG**	**STRONG**	OK	OK	**STRONG**	*Weak*
Visual 2D	OK	**STRONG**	**STRONG**	OK	**STRONG**	**STRONG**	OK	OK	OK	OK
Visual 3D	*Weak*	OK	OK	OK	OK	OK	OK	**STRONG**	**STRONG**	**STRONG**
Kinesthetic	*Weak*	*Weak*	*Weak*	*Weak*	OK	**STRONG**	OK	**STRONG**	**STRONG**	**STRONG**
ALIGNMENT OF MULTIPLE REPRESENTATIONS										
Spatial: Content is present in the same space as other related content	OK	**STRONG**	OK	OK	OK	OK	**STRONG**	**STRONG**	**STRONG**	**STRONG**
Temporal: Content is presented or adapted when relevant to the student's activity	*Weak*	*Weak*	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**
SUPPORT FOR EMBODIMENT										
Student learns about spatial locations by moving body between physical locations	*Weak*	*Weak*	*Weak*	*Weak*	OK	OK	OK	**STRONG**	OK	**STRONG**
Student learns about physical entities by mimicking the movement of entities with their body	*Weak*	*Weak*	*Weak*	*Weak*	*OK*	**STRONG**	*Weak*	*Weak*	**STRONG**	OK
Student learns about abstract entities by enacting embodied metaphors	*Weak*	*Weak*	*Weak*	*Weak*	*OK*	**STRONG**	*Weak*	*Weak*	**STRONG**	OK
DIRECTED ATTENTION Media highlights specific content to scaffold student learning.	*Weak*	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**
INTERACTIVE SIMULATION Students can interact with visualized phenomena.	*Weak*	*Weak*	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**	**STRONG**
MEDIA IS ACCESSIBLE TO LARGE POPULATION	**STRONG**	**STRONG**	**STRONG**	OK	*Weak*	*Weak*	OK	OK	OK	*Weak*
MEDIA FACILITATES COLLABORATION	*Weak*	*Weak*	*Weak*	OK	**STRONG**	*Weak*	*Weak*	OK	OK	**STRONG**

The table serves to differentiate between mediums, highlighting factors potentially beneficial for learning in augmented reality experiences. In the subsequent sections, selected factors are discussed in more detail. The discussion is focused on specific factors that can be strongly present in AR experiences. These factors are discussed in relation to research fields such as education, interaction design for children, and cognitive and developmental psychology, which have highlighted the beneficial learning effects from each factor. It is worth noting that each of these factors has the potential to aid learning and may be present in an AR application; however, it is worth stressing again that the design of the AR application will impact how strongly each factor influences the user's learning.

Content is represented in novel ways

In educational contexts, knowledge is typically learned from visual, auditory and sometimes tactile representations. Paper-based textbooks carry static visual content, such as text and diagrams. Through digital media (where computers output interactive graphics to monitors, projectors or AR displays), content can be presented in a variety of other forms: static images become animations, 2D representations become 3D objects, text becomes sound, and non-interactive content becomes interactive. All these changes in representation can be educationally effective, as information becomes easier to process and appeals to different learning styles [39].

Augmented reality provides additional benefits over PC-based media. The limitation of desktop PCs are that interaction is typically limited to mouse and keyboard, an interaction which is potentially difficult to learn, and which may not invoke a strong feeling of student presence in the learning environment. Also, the desktop output is on a two-dimensional screen, making understanding and interaction with 3D content unnatural. Extending beyond the capabilities of desktop-based media, AR allows students to visualize complex 3D content in their own physical environment, and leverage gestural interaction. The medium of AR can thus present educational content through representations of life-like 3D objects and body-based metaphors, potentially reaching learners through novel modalities and causing deeper learning.

Multiple representations appear at the appropriate time / space

Mayer's multimedia learning theory, summarized in [39], posits that the human brain has limited capacity for processing information from sensory channels (thus, too much information results in cognitive overload and is detrimental to learning), and that processing of sensory information is processed separately according to its modality (eg: verbal information is processed separately from, and in parallel to, pictorial information).

Mayer presents two constructs useful to understanding the educational benefits of electronic media: The *spatial contiguity effect* indicates that students learn better when multiple representations of the same information are presented close together in space rather than far apart. (For example, when observing a diagram, it is more effective to present labeled objects within the figure, rather than to put the labels within a separate legend or text description). The *temporal contiguity effect* indicates that students learn better when multiple representations of the same information are presented at the same time, rather than separated in time. (For example, when

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visually observing a phenomenon, it's more effective to receive auditory information in the context of observation rather than after the observation).

Within AR, information can be spatio- and temporally- aligned with physical items and with the learner's activities. The learning experience becomes tied to the physical world and to meaningful objects in the learner's environment. The system can monitor the user's activities and bring relevant information in context, scaffolding learning, and reducing the need for learner to switch attention between different media or to mentally transform representations [8, 28]. Further, multiple representations about the same physical phenomenon can be displayed at the same time, allowing learners to correlate between representations.

The learner is physically enacting the educational concepts

Several papers report that user's memory is better for content presented with AR than non-AR. The enhanced memory encoding may be caused by the physical immersion of AR experiences, and the fact that users interact by moving their body and limbs, which potentially cause learners to encode tactile and proprioceptive information along with the educational content [17].

Research shows that physical activity is linked to conceptual understanding of educational content: Shelton and Hedley, in their studies of spatial learning in AR [40], hypothesize that visuo-spatial comprehension is enhanced by physical interaction with 3D content. Research on gestural communication by Goldin-Meadow and colleagues [41], indicates that when students had to use gestures in solving math problems, they learned better than students who did not use gestures. Glenberg [42] indicates that elementary-school students learn a story better when they use their hands to act scenes from the story. Further, Roth and Lawless [43] show that when students discuss a physical phenomenon (such as electron movement), using gestures is helpful in gaining abstract understanding of the phenomenon.

Additionally, embodied cognition research indicates that mixed-reality technology can be designed such that students physically enacting an abstract concept, such as the concept of balance [44] or mathematical ratios [45], and that these experiences have the power to change student understanding.

Physical interactivity through augmented reality is strongly suited for leveraging learning through embodied interactions, as these affordances are not strongly present when students interact with other media such as books or desktop PCs. In light of this research, there emerge three potential groups of applications of augmented reality to embodied learning: (1) games can be designed whereby students must move their body to different spatial locations (eg: tracing the path of an electron with their finger); (2) games can require students to enact important entities (eg: the student becomes the bat, flapping their hands like a bat); and (3) games can require students to enact abstract concepts (eg: students can enact the concept of addition as a construction activity, by piecing two numbers together into a larger number).

Attention is directed to relevant content

The "digital augmentation" of reality can direct the user's attention to relevant content. This feature is most apparent in physical assembly tasks, where AR effectively guides attention by highlighting important components. This mechanism effectively transfers to other learning tasks involving visuo-spatial information. The system presented by Nischelwitzer and colleagues [22], highlights important organs in order to effectively teach students about the 3D configuration of organs inside the human body.

This attention-directing benefit is not limited to AR applications alone. Mautone & Mayer [46] indicate that educational instruction can use both speech tone and visual indicators to highlight important pieces of information in a 2-dimensional animation, and such cases lead to enhanced student learning.

However, augmented reality games can leverage this mechanism in order to focus student attention on important aspects of their environment, for instance an outdoor game that points at geometric shapes or patterns in the physical space, thus making the educational content more relevant to the user's immediate surroundings.

The learner is interacting with a 3D simulation

AR learning applications are essentially interactive digital simulations. Digital simulations in general are effective tools because they allow students to experience phenomena that are impossible or infeasible to experience otherwise (such as allowing students to change spatial scales to see a functioning solar system [37], or speeding time to watch plant growth [47]), they are dynamic and interactive allowing student control over the educational content (such as playing with chemical reactions [21]), and they scaffold and assess user learning (as in the organ simulation system in [22]).

These affordances for learning are not limited to AR systems, and they can be present in any computer-based simulation. The benefit of AR specifically is that it allows users to be immersed in the simulations [48], to easily collaborate with others around simulations by leveraging non-verbal cues [32], and to leverage the benefits of simulations in understanding complex 3D phenomena that would be difficult to comprehend through other media [49].

Interaction and collaboration are natural

AR systems are generally easy to use by even young students, because students can use their body to manipulate the content, transferring knowledge and interactions from the real world into the experience, rather than having to learn to use the system [50]. Furthermore, embodied interfaces appear to be inherently motivational for users. The motivational benefits and ease-of-use of most AR systems can reduce cognitive load, and encourage student exploration and creativity [33].

Interestingly, one study finds that children reported wanting to continue playing with the AR version of an application, even when the non-AR version was easier to use [34]. This indicates that ease of use is not a single determining factor in user engagement, and that, when students are

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motivated to engage with the experience, they will use it even if they must overcome some challenges with ease of use. According to flow theory [51], there are multiple factors that influence engagement, such as the availability of clear feedback, the availability of internal goals, and a balance between challenge and personal skills. With young children, there are also other factors contributing to engagement, such as the attractiveness of graphics and the complexity of the storytelling. Ease of use may play a positive or negative role in contributing to user engagement. On one hand, the difficulty of using an interface may reduce user engagement, but this difficulty may be outweighed by other factors that motivate the user to continue experiencing the application. On the other hand, the difficulty of using an interface may contribute to the challenge of the experience, and may therefore contribute to the user's engagement – this latter point is visible in video games that are deliberately created to be difficult to use.

Heuristic Questionnaire

By accounting for the factors identified above, a heuristic questionnaire has been constructed to identify applications that maximize learning potential of the AR medium. Currently, the list is composed of the following statements, evaluated on a scale of 1 (Strong Disagree) to 5 (Strong Agree):

1. The application transforms the problem representation such that difficult concepts are easier to understand.
2. The application presents relevant educational information at the appropriate time and place, providing easy access to information and/or reducing extraneous learner tasks.
3. The application directs learner attention to important aspects of the educational experience.
4. The application enables learners to physically enact, or to feel physically immersed in, the educational concepts.
5. The application permits students to interact with spatially-challenging phenomena.

The above heuristic questionnaire has not been formally evaluated. Plans for future work involve using the questionnaire to score existing AR experiences, and determining whether the questionnaire scores correlates to the observed learning gains of users.

Conclusion and Future Work

Through the literature review of 26 comparative AR publications, this analysis has identified several positive and negative effects of AR on learning, as well as potential factors underlying these effects. Future work can further develop the heuristic questionnaire, and validate its usefulness in helping to identify educational AR experiences.

As mentioned above, the factors and effects discussed in this paper are mediated by the unique design of each augmented-reality experience. Future work can investigate how AR designers can maximize the potential learning benefits, and generate guidelines for designing effective educational AR experiences. A related direction for future work is identifying other factors which may be beneficial in AR experiences but which have not been accounted in the above analysis, such as improving teacher support by providing facilities for customizing content and monitoring student learning.

Furthermore, the interaction of student learning and human developmental factors should be taken into account, such as investigating how student's developing cognition, motor and spatial skills influence their ability to use and understanding AR-based educational content. An initial step in this research direction is addressed by author's previous work in [52], which discusses how young children's psychological and physiological development influence their ability to use AR applications.

Another avenue for future work is to determine what types of content can be effectively taught using AR, and what type of content is difficult. For example, the above analysis indicates that AR provides opportunities for teaching 3D spatial and kinesthetic content, but that AR may not be fit for textual content or 2D simulations. It is important for future research to acknowledge the limitations of AR technology, and to study the types of educational experiences this medium is suitable or unsuitable for.

There are also several topics that need to be addressed in order to ease the adoption of this technology into school classrooms. First, AR experiences need to be designed with curriculum and pedagogy in mind. Future research must identify curriculum topics are currently difficult to teach using other media, and are worth the investment cost for AR. AR technology designers must also understand how to create experiences that integrate into classroom pedagogy, such as structuring AR content so it can be integrated into multiple points along the curriculum, designing for multiplayer AR experiences so students can collaborate, designing experiences that can be tailored by teachers to custom fit their curriculum, designing intelligent applications that monitor and adapt to student progress, and designing AR applications that integrate with existing content such as textbooks and learning games.

Further, future work can investigate the investment costs for teacher training, as well as investments in hardware and other infrastructure required to integrate AR in classrooms. Investments vary depending on the platform used, as AR experiences may be displayed with a classroom projector or interactive whiteboard, or may be executed on student's personal devices. There are also space considerations, because, due to the high degree of physical interaction, AR experiences typically require a larger space than computer experiences. Finally, classroom applications will typically benefit from networked connectivity, such that students can collaborate around virtual content, and so that teachers can monitor and control the experience; thus, requiring infrastructure for wireless networking.

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