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The Use of Augmented Reality in Formal Education: A Scoping Review

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ABSTRACT

Augmented Reality (AR) is recognized as one of the most important developments in educational technology for both higher and K-12 education as emphasized in Horizon report (Johnson et al., 2016, 2015). Furthermore, AR is expected to achieve widespread adoption that will take two to three years in higher education and four to five years in K-12 education (Johnson et al., 2016, 2012). If this is the current state of the art for the use of AR in education, it is important to investigate how educators and researchers integrate AR into teaching-learning processes. Looking from such a glimpse, the purpose of this scoping review was to provide a comprehensive overview of relevant research regarding the emergence of augmented reality, the links to pedagogy and educational outcomes, specifically in the context of formal education. The scoping review is underpinned by the five-stage framework Arksey and O'Malley (2005). First, research questions are identified. Second, the last five years in ERIC database is explored by using the search term 'augmented reality.' Third, studies are investigated through inclusion and exclusion criteria, and PRISMA (2009) model is utilized for article selection. Fourth, selected articles are charted with respect to numerous dimensions and summaries. Finally, findings are reported in the light of research questions. The findings of the scoping review illustrated a set of studies that provide evidence of improved academic performance, increase in students' engagement, motivation, and satisfaction through the educational environments that are enriched with AR applications. The findings of the scoping review are discussed with respect to multiple dimensions that are explored under research questions.

Keywords: augmented reality, scoping review, higher education, K-12, formal education.

INTRODUCTION

Education in specific fields of study or skill might take place in various ways (Lee, 2012). Furthermore, education can be circled around different forms of media, ranging from non-interactive books to highly interactive ones that might arouse a wide variety of senses (Radu, 2014). Yet, one of the most important central considerations for educators is the dynamic means of content delivery through the enhancement of instructional practices (Thornton,

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State of the literature

- As an emerging technology, Augmented Reality (AR) is expected to achieve widespread adoption in teaching-learning processes.
- Hence, a clear need accrues in how AR applications are being adopted within teaching-learning processes, particularly in formal education.
- This study aims to provide a comprehensive overview of the current state of the art for the use of AR in formal education.

Contribution of this paper to the literature

- The study provides an insight regarding how AR applications are being adopted in formal education.
- Revealing both benefits and implications of the use of AR in formal education might improve the process of how AR should be integrated with educational settings.
- This scoping review reveals the need for stronger evidence to create a conventional wisdom on the use of AR in formal education.

Ernst, & Clark, 2012). As an emerging technology (Martin-Gonzalez, Chi-Poot, & Uc-Cetina, 2015; Johnson et al., 2014; Van Arnhem, & Spiller, 2014), Augmented Reality (AR) not only supplements the dynamic notion of the instructional practices (Thornton, Ernst, & Clark, 2012) but also incorporates sensory modalities, such as, touch, sight and hearing (Pérez-López & Contero, 2013). Except supplementing a wide variety of sensory modalities, there is a vast amount of research on revealing the potential benefits of the use of AR in formal education, such as, improving students' academic achievement (Estapa, & Nadolny, 2015; Lu, & Liu, 2015; Civelek, Ucar, Ustunel, & Aydın, 2014), motivation (Ferrer-Torregrosa et al. 2015), knowledge retention (Pérez-López, & Contero, 2013), and engagement (Bressler, & Bodzin, 2013; Zarraonandia, Aedo, Díaz, & Montero, 2013). To achieve such critical learning outcomes during the teaching-learning processes, Thornton, Ernst, & Clark (2012) suggest that educators must constantly utilize 'contemporary and cutting-edge' technological applications, one of which is AR.

AR is defined as having three main characteristics: (1) combination of real and virtual, (2) real-time interactivity, and (3) 3D registration (Azuma, 1997). AR applications supplement the real world by incorporating virtual or computer-generated content (Azuma et al., 2001). According to Azuma (1997) rather than replacing the reality, AR supplements it. AR applications are categorized into two different groups with respect to technologies that they use; marker-based and marker-less (Carbonell Carrera, & Bermejo Asensio, 2016). In marker-based AR applications, symbolic figures are perceived by a computer through a marker and a camera in a way that virtual information is presented to the users (Carbonell Carrera, & Bermejo Asensio, 2016). In marker-less applications, for instance in location-based AR applications, user's real-world location is gathered through GPS technology and contextually relevant virtual data are provided to the user at geographically significant locations. (Bower, Howe, McCredie, Robinson, & Grover, 2014). Current research on the use of AR applications in formal education highlights the fact that such applications have a positive impact on learning and learners' attitudes (Lu, & Liu, 2015; Martin-Gonzalez et al., 2015). According to the report of New Media Consortium (Johnson et al., 2015) AR is viewed as having numerous potentials to change educational settings, such as, enhancing progressive pedagogies, instructional strategies, and the arrangement and delivery of content. Furthermore, the use of AR applications is considered to improve students' cognition and interaction which results in more effective learning (Lu, & Liu, 2015). While the motivation or achievement of skill is recognized as an important reason for the development of teaching tools (Ferrer-Torregrosa et al., 2015), as in the case of AR applications, educators should also take consideration into the idea of how such applications might be integrated with instructional strategies or pedagogical approaches in formal education. Studies revealed that the use of AR in formal education might enable educators to combine those applications with various pedagogical approaches, such as, situated learning (Chang, & Jen-ch'iang, 2013; Chang, Wu, & Hsu, 2013; Crandall et al., 2015; Estapa, & Nadolny, 2015), inquiry-based learning (Wang et al., 2014; Bressler, & Bodzin, 2013; Chang, Wu, & Hsu, 2013), and game-based learning (Hwang et al. 2015; Lu, & Liu, 2015; Bressler, & Bodzin, 2013).

The value (Chen, & Wang, 2015) and importance (Lee, 2012) of using AR applications in formal education is studied with respect to various learning outcomes. For instance, researchers investigated whether AR enhanced multimedia learning improves the retention of the delivered content, and found that students using AR multimedia contents improved knowledge retention as opposed to those following a traditional course (Pérez-López, & Contero, 2013). In a study, AR enhanced and traditional 2D simulation systems are compared whether such systems lead a better collaborative inquiry learning behaviors on the topic of elastic collision among university students (Wang et al., 2014). Researchers found that AR simulation leads a more supportive role in students' collaborative inquiry learning than traditional learning (Wang et al., 2014). In a media comparison study, researchers investigated how different forms of technological mediation (computer vs. robot) might have an impact on kindergarten students' perception toward AR-infused dramatic play (Han, Jo, Hyun, & So, 2015). The results indicated that regardless of the media type, younger children tended to have higher satisfaction with AR-infused dramatic play (Han, Jo, Hyun, & So, 2015). In another research, McMahon, Cihak, & Wright (2015) compared the instructional effectiveness of a location-based AR navigation tool with Google maps and print based material on students diagnosed with intellectual disability or autism spectrum disorder. Researchers found that students were better in travelling with the help of location based AR navigation tool (McMahon, Cihak, & Wright, 2015).

In a systematic review of research and applications, the use of AR in education was found to be effective for several purposes, such as a better learning performance, learning motivation, student engagement and positive attitudes (Bacca et al., 2014). The effective integration of emerging technologies, like AR, has several challenges requiring the need for overcoming numerous impediments (Martins, Gomes, & de Paiva Guimarães, 2015), such as, integration into traditional learning methods, costs for the development and maintenance of the AR system, and general resistance to new technologies (Lee, K., 2012). Moreover, the effective design of AR applications (Estapa, & Nadolny, 2015; Tanner, Karas, & Schofield, 2014) and technical thresholds (Garrett, Jackson, & Wilson, 2015; Lu, & Liu, 2015; Tanner, Karas, & Schofield, 2014; Chang, & Jen-ch'iang, 2013) are considered to have an inhibitor effect for educators during the integration process. Notwithstanding, it is still recommended that there is a need for ongoing exploration (Estapa, & Nadolny, 2015; Bacca, Baldiris, Fabregat, & Graf, 2014) to determine and create a 'conventional wisdom' in that either new media or technologies, such as AR applications, and pedagogical approaches or methods together have positive effects on students' learning outcomes.

Looking from such a glimpse, the purpose of this scoping review is to capture the relevant research studies in the literature on the use of AR in formal education. The study may reveal the point that how educators and researchers approach integrating AR applications into teaching-learning processes.

To be able to filter studies as formal, informal or non-formal education, following definitions are selected to guide the process. Formal learning is accepted as contexts in which learning takes place in a planned and structured way, non-formal learning is considered to occur in meaningful contexts, like libraries, zoos, or museums, and informal learning is considered to result from daily life or leisure activities (as cited in Hsiao, Chang, Lin, & Wang, 2016).

METHOD

This is a scoping review study in which Arksey and O'Malley's (2005) five-stage framework is utilized. The five stages of Arksey and O'Malley's framework; (1) identifying research questions, (2) identifying relevant studies, (3) study selection, (4) charting the data, (5) summarizing and reporting the results were utilized in this review of the use of AR in formal education.

Identifying research questions

The focus of the review was the exploration of key aspects of the use of AR applications, specifically in the context of formal education, that influence the effectiveness of teaching-learning processes and student learning experiences. To ensure that a substantial range of literature was captured relating to the topic of interest, following research questions are posed to guide the research:

1. What technologies are being used in AR applications?
2. What kind of pedagogical approaches are being integrated with AR applications?
3. What are the affordances of AR applications in formal education?
4. What are the educational outcomes arising from the use of AR applications?
5. What limitations are outlined regarding the use of AR applications?

Identifying relevant studies

To cover a broad range of studies regarding the use of AR in formal education, the search term 'augmented reality' is selected. The reason for selecting 'augmented reality' as a search term without applying any other filtering options was to reach out studies as much diverse as possible. Afterwards, inclusion and exclusion criteria were developed. Such a step was followed by analyzing several literature review studies to be able to get deeper insights regarding the dimensions that can be included to summarize the selected researches. After several literature review studies are examined and analyzed (see Koutromanos, Sofos, & Avraamidou, 2015; O'Flaherty, & Phillips, 2015; Bacca, Baldiris, Fabregat, & Graf, 2014), variables for either inclusion or exclusion are determined. **Table 1** illustrates the cases for inclusion and exclusion criteria. The last 5 years has seen the integration of augmented reality applications into educational institutions more frequently. As a result, the last 5 years was considered appropriate, since such a time period is likely to reflect the specific use of augmented reality in formal education. The electronic database ERIC is searched to identify the researches in the light of inclusion and exclusion criteria. The reason for researchers to go over and search through ERIC database was because of it publishes current and cutting-edge education related resources (ERIC, 2016). Since the purpose of this scoping review is to cover education related researches on the use of AR in formal education, ERIC is considered to be an appropriate database to reflect the current predisposition.

Table 1. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Time period	The last 5 years (2012 - 2016)	Studies outside these dates or time period
Study Focus	Formal education context (e.g. higher, secondary education)	Studies that are carried out in informal or non-formal learning contexts
Literature Focus	Studies relating specifically to the formal education context, activities, and learning outcomes (e.g. students' academic achievement, motivation, knowledge acquisition, knowledge retention, satisfaction)	Researches that only designed an AR application but did not apply in a formal education context, studies just mentions about merit of AR, previews of thesis and dissertations
Sample	Students continuing in formal education settings where an AR application is integrated with or applied in teaching-learning process	Informal or non-formal learning purposes of AR on adults, tourists or visitors in a museum or in a zoo, and all other informal sample in which there is no educational or learning outcome

Study selection

Using the key search term; that is 'augmented reality' in ERIC database, a wide variety of studies are reached to be reviewed. ERIC database is searched on March 22, 2016 and 102 articles were identified that were published between 2012 and 2016. A review of the titles and the abstracts revealed the fact that a large number of articles were irrelevant, particularly those related to initiation of AR systems, and the suggestions for the potential use of AR in education. Studies that are carried out in an informal education context are also excluded since there were no education related learning outcomes. Examples include studies that detailed reports on the use of AR applications in library, museum or zoo services. Furthermore, reviewing wide variety of studies provided a glance for excluding similar researches, like the design and development of AR tools, and technical dimensions of AR applications. The process of article selection followed the PRISMA (2009) model (Moher, Liberate, Tetzlaff, Altman, & The PRISMA Group, 2009). **Figure 1** below represents the process of article selection step by step.

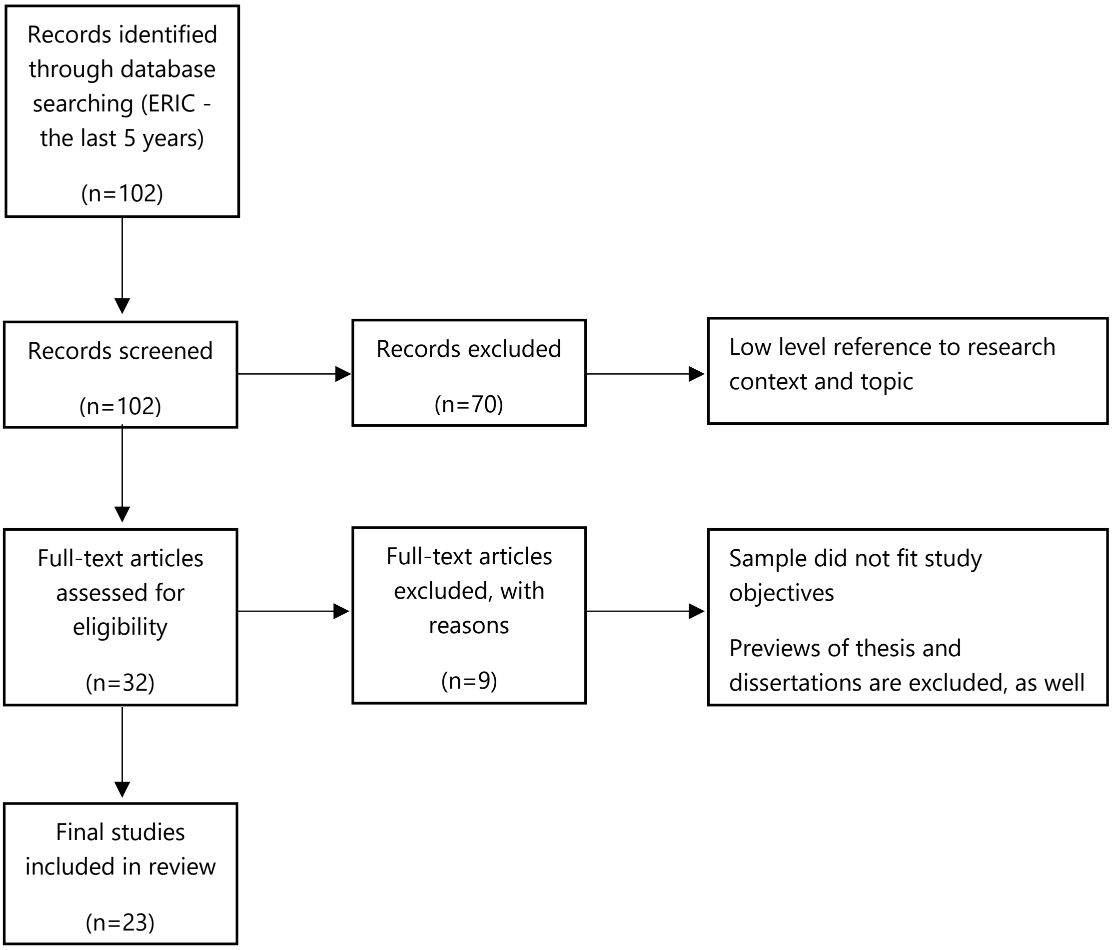

Figure 1. PRISMA flow diagram for article selection.

Charting of Data

The fourth step was the charting of selected articles. After each study is considered to be included in the light of inclusion and exclusion criteria, summaries are developed for each article with respect to numerous dimensions, such as the author, year, AR features, affordances, pedagogical approaches, results, limitations and suggestions. A detailed summary of those variables that are concluded from the included studies are illustrated in **Table 2.**

Table 2. Studies Included into Scoping Review

Author	(1) Estapa, A., & Nadolny, L. (2015) - USA	(2) Tanner, P., Karas, C., & Schofield, D. (2014) - USA	(3) Gomes et al. (2014) - Portugal	(4) Enyedy, N., Danish, J. A., & DeLiema, D. (2015) - USA	(5) Lu, S., & Liu, Y. (2015) - Taiwan
Sample	K-12 / 61 students	K-12 / 19 studnets	K-12	K-12	K-12 / 51 students
AR Features	Print-based	Print-based	Location-based	Location-based	Gesture-based, Marker-based
Affordances	Technical and conceptual change	Comprehension of a procedural task	Knowledge acquisition	Concept development	Concept development
Pedagogical Approaches	Situated learning	No pedagogical approach is recognized.	Collaborative learning	Sociodramatic play	Game-based learning
Results	More effective in getting students' attention	Higher level of comprehension. No evidence for more engaged students in AR context. 90% of the students would preferred the traditional static manual over AR enhanced. AR application is found to be difficult to use and understand.	High levels of enthusiasm and engagement. Contribution to added interest and motivation towards learning and scholarship outcomes.	Helping elementary students to explore physics concepts by developing liminal blends was invaluable.	Higher confidence and satisfaction, knowledge acquisition, improve in learning performance of low achievers. Keeps students lively and active, and eager to participate with their peers.
Limitations	Small sample size and data sources were restricted to a survey and test format.	Malfunction by the application leading decreased learnability for the animated manual.	No limitation is recognized.	No limitation is recognized.	Numerous technical threshold, and teachers' inability to develop resources successfully.
Suggestions	Need for further exploration on learning outcomes. The distraction factor should be considered during the design process. The impact of optimal design elements on students' learning might be investigated.	Usability issues should be investigated in AR applications. Smaller devices are recommended to search on AR applications.	Need for further exploration on the potential benefits on knowledge acquisition, motivation and engagement.	Cultural and material factors should be considered during physical actions in an AR environment.	Needs to be a cooperation with engineers for the development of resources. There might be a need for teaching assistance during the process.

Table 2. (*Continued*)

Author	(6) Crandall et al. (2015) - USA	(7) Ferrer-Torregrosa et al. (2014) - Spain	(8) Lin, H. C. K., Chen, M. C., & Chang, C. K. (2015) - Taiwan	(9) Pérez-López, D., & Contero, M. (2013) - Spain	(10) Chen, C. P., & Wang, C. H. (2015) - Taiwan	(11) Han, J., Jo, M., Hyun, E., & So, H. J. (2015) - Korea
Sample	Higher Education / 48 students	Higher Education / 211 students	K-12 / 76 students	K-12 / 39 students	K-12 / 144 students	K-12 / 81 children
AR Features	Location-based	Print-based	Image-based	Marker-based	Image-based	Marker-based
Affordances	Concept development	Concept acquisition	Concept acquisition	Knowledge retention	Concept development	Dramatic play
Pedagogical Approaches	Game-based learning, situated and constructivist learning	No pedagogical approach is recognized.	No pedagogical approach is recognized.	No pedagogical approach is recognized.	No pedagogical approach is recognized.	Media comparison
Results	There was unanimous preference from participants in favor of using the game-based learning as opposed to the standard lecture.	Better scorings on attention-motivation, autonomous work and three-dimensional comprehension tasks. Better scoring in the written test for the ARBOOK. Improved spatial comprehension.	Students' performances from the AR-assisted teaching improved, yet there was not a significant difference between the groups. Students with average and low academic achievements benefit the most.	Increase in knowledge retention, interest and attention. Easier to follow and better behaviors during the lessons. Higher preference toward the use AR. With respect to usability, higher preference for AR applications.	Better learning achievement and playing with the AR toolkit was either interesting or valuable.	Regardless of the media type, higher satisfaction with AR-infused dramatic play.
Limitations	Technical limitations, such as GPS functions on mobile devices.	No limitation is recognized.	No limitation is recognized.	No limitation is recognized.	Generalizability of the research findings is restrained because of limited subject matter.	Small sample size and the duration of the application.
Suggestions	AR applications might be considered in case there is no appropriate lab space.	More studies must be addressed in order to assess other unexplored possibilities of the ARBOOK tool.	Concerning study samples, a larger sample should be used to obtain a more complete statistical dataset. Lengthening the research timeframe is also recommended.	Need for more extensive research on the use of AR applications.	Larger sample sizes and extensive subject matters are the two recommendations.	Need for longer period of time in experimenting.

Table 2. (*Continued*)

Author	(12) Wang et al. (2014) - Taiwan	(13) McMahon, D., Cihak, D. F., & Wright, R. (2015) - USA	(14) Hsiao et al. (2016) - Taiwan	(15) McMahon et al. (2016) - USA	(16) Civelek et al. (2014) - Turkey	(17) Chang, Y. H., & Jen-ch'iang, L. I. U. (2013) - Taiwan
Sample	Higher Education / 40 students	Higher Education / 4 students	K-12 / 64 students	Higher Education / 4 students	K-12 / 215 students	Graduate students
AR Features	Marker-based	Location-based (Geo-based)	Image-based	Marker-based	Haptic based	Marker-based
Affordances	Concept development	Knowledge acquisition	Academic achievement	Knowledge acquisition	Knowledge acquisition	Knowledge acquisition
Pedagogical Approaches	Collaborative inquiry learning	Media comparison	Learning tool comparison	No pedagogical approach is recognized.	No pedagogical approach is recognized.	Situated learning theory
Results	More supportive in students' collaborative inquiry learning. More appropriate for students to conduct inquiry tasks collaboratively. AR applications lead a more authentic learning environments.	Improvement in students' success in traveling over other methods. More effective way of communication. Higher preference toward AR application. No need for person-supported assistance in AR application. More enjoying.	Greater positive impact on students' academic achievement and motivation. Higher creativity on students' inquiry-based learning. Increase in interest to use the application for learning.	Using AR to learn vocabulary words was socially acceptable. Students enjoyed using the AR. AR application was an effective strategy for vocabulary acquisition for all the students.	Positive effects on students' achievement, motivation, encouragement, autonomy, and learning quality.	Appreciation and satisfaction of the overall quality of the content using AR. Greater learning achievement between the experimental and control group.
Limitations	Random errors should be incorporated with application to enhance students' critical thinking.	Small sample size. Travelling alone might change the results due to safety consideration.	Whether manipulative interactive tool or AR application improved the academic achievement is not known.	Small sample size. AR might create a novelty effect on students' learning.	Including only posttest design and small number of girls may comprise a limitation.	Getting and producing 3D objects more conveniently is required. Easy to use applications with both hands or even with one is needed.
Suggestions	Design considerations should be carefully organized for scaffolds. AR and physical experimentations can be mixed to investigate the influences on students' learning.	Generalizability of the results should be improved by applying to various samples, context or with a larger population, as well as investigating the advantages and disadvantages of using AR on students with disabilities.	Make it easy to use, include manipulative aids (interactivity, entertainment, usefulness).	Need for longer term effects. Internet connection should be keep in mind during the application. Need for replication studies. Which AR features lead to positive outcomes without distracting the learner should be further explored.	Need for further research on students' academic achievement and motivation. Assigning groups randomly and conducting a true experimental design is needed. Multiple schools, contexts, and qualitative research might be used.	Ease of use for AR applications should be improved and strengthened. System usability must be improved.

Table 2. (*Continued*)

Author	(18) Hsiao, K. F., Chen, N. S., & Huang, S. Y. (2012) - Taiwan	(19) Chang, H. Y., Wu, H. K., & Hsu, Y. S. (2013) - Taiwan	(20) Garrett et al. (2015) - Canada	(21) Zarraonandia et al. (2013) - Spain	(22) Bressler, D. M., & Bodzin, A. M. (2013) - USA	(23) Borrero, A. M., & Márquez, J. A. (2012) - Spain
Sample	K-12 / 1211 students	K-12 / 22 students	Higher education / 72 students	Higher education / 11 students and 1 lecturer	K-12 / 68 students	Higher Education / 20 students and 10 teachers
AR Features	Gesture-based	Marker-based	Marker-based	Marker-based	Marker-based	Marker-based
Affordances	Learning while exercising	Knowledge comprehension	Knowledge acquisition	Enhancing the feedback loop	Increase in interest	Enable remote lab experience
Pedagogical Approaches	Constructivist and game-based learning	Inquiry-based learning, situated learning	Constructivist heuristic learning	No pedagogical approach is recognized.	Flow theory, inquiry based learning, game based learning	No pedagogical approach is recognized.
Results	Students in AR enhanced group had the highest scores with respect to "Usefulness of Learning Ecosystems" and "Anxiety in Learning Ecosystems"	The combination of AR and inquiry activities promotes students' understanding of the science content effectively. Students had positive perceptions toward AR enhanced activities.	Positive attributes, such as access to resources and self-directed learning, were recognized by students and faculty. Students' overall perspectives regarding AR application was positive.	AR enhanced feedback practice fosters communication and interaction during lectures and might enhance engagement in the activities. Positive opinions regarding AR application both for students and lecturer.	Increase in interest and collaboration skills. AR is viewed as a scalable design for schools.	Higher scores in AR enhanced applications facilitate better learning. No difficulty is encountered in integrating AR applications into laboratory practices.
Limitations	Environment constraints, curriculum design, unfamiliarity with the operation of the system.	The sample size is small, and future studies are needed to generalize the exploratory findings of this study.	Technical limitations: slow response time, scanning and internet problems, incompatible smartphones. Small sample size.	The context of one single lecture with a reduced number of students.	One single sample should be taken into consideration when generalizing to other contexts.	No limitation is recognized.
Suggestions	A good guide book for AR teaching directions particularly for teacher use might be useful. Curriculum design must be followed as it is defined. Novelty effects should be reduced by providing sufficient familiarity.	Future studies need to investigate other important aspects such as moral reasoning in an AR-enhanced SSI learning environment	Further research studies are needed to achieve the practical value of the use of AR.	Further research studies in larger classes and during many lectures is warranted.	Gender issues might be explored through various group distributions. Short-term and long-term influence might be explored.	Future research shall focus on extending its applications to other engineering fields.

Summarizing and reporting findings

The final step of the scoping review was to summarize and report findings in the light of steps that are followed. Developing summaries of each study made reporting of the findings easier to follow and discuss in the light of research questions.

FINDINGS

This scoping review covered 23 research studies from numerous countries. Of these, 8 studies were conducted in Taiwan, 7 in the United States, 4 in Spain, 1 in Turkey, 1 in Portugal, 1 in Canada and 1 in Korea. In this section of the study, research questions are discussed by illustrating relevant studies included into the scoping review. Selected studies are discussed regarding the technologies used in AR applications, kinds of pedagogical approaches integrated with AR applications, affordances of AR applications in formal education, educational outcomes arising from the use of AR applications and limitations outlined regarding the use of AR applications in education.

What technologies are being used to engage students in AR applications?

The majority of the studies utilized marker-based technology for integrating AR applications into teaching-learning processes. **Table 3** illustrates the AR technology used within the studies that are included into this scoping review.

Table 3. AR technologies used in the studies

Study Number	Print-based	Marker-based	Location-based	Gesture-based	Image-based	Haptic-based
1, 2, 7	✓					
5, 9, 11, 12, 15, 17, 19, 20, 21, 22, 23		✓				
3, 4, 6, 13			✓			
5, 18				✓		
8, 10, 14					✓	
16						✓

As it is illustrated in **Table 3**, AR technologies that are used in the studies are print-based (1, 2, 7), marker-based (5, 9, 11, 12, 15, 17, 19, 20, 21, 22, 23), location-based (3, 4, 6, 13), gesture-based (5, 18), image-based (8, 10, 14) and haptic-based (16).

What kind of pedagogical approaches are being integrated with AR applications?

There were few studies that integrated AR applications with a pedagogical approach or instructional strategy. The majority of the studies did not determine and use a pedagogical approach, but instead they just focused on integrating AR applications into activities on the curriculum and evaluated the findings with respect to educational outcomes, especially by gathering students' perspectives regarding the use of AR applications. **Table 4** illustrates the studies that integrated pedagogical approaches into AR applications during the teaching-learning process.

Table 4. Pedagogical approaches integrated into AR applications

Study Number	Situated Learning	Inquiry-based Learning	Collaborative Learning	Game-based Learning
1, 6, 17, 19,	✓			
11, 19, 22		✓		
3, 11			✓	
5, 6, 22				✓

As it is illustrated in **Table 4**, pedagogical approaches integrated into AR applications are situated learning (1, 6, 17, 19), inquiry-based learning (11, 19, 22), collaborative learning (3, 11), and game-based learning (5, 6, 22).

What are the affordances of AR applications in formal education?

AR applications are intended to afford several learning outcomes before they are applied to the real teaching-learning processes. Knowledge comprehension/acquisition, concept development, and knowledge retention are amongst the affordances that researchers attributed to the use of AR applications. **Table 5** illustrates the affordances of AR applications by referencing the studies included into this scoping review.

Table 5. Affordances of AR applications

Affordances of AR	Study Number
Knowledge comprehension / acquisition	2, 3, 7, 13, 15, 16, 17, 18, 19
Concept development	1, 5, 6, 10, 12
Knowledge retention	9

As it is illustrated in **Table 5**, affordance of AR applications are knowledge comprehension / acquisition (2, 3, 7, 13, 15, 16, 17, 18, and 19), concept development (1, 5, 6, 10, and 12) and knowledge retention (9).

What are the educational outcomes arising from the use of AR applications?

The findings of the scoping review illustrated a set of studies that provides evidence of improvement in students' educational outcomes with respect to numerous dimensions. **Table 6** illustrates those dimensions aroused from the usage of AR applications.

Table 6. Educational outcomes arising from the use of AR applications

Educational Outcomes	Study Number
Attention	1, 7, 9
Engagement	3, 21
Interest	3, 9, 10, 14, 22
Motivation	3, 7, 16
Satisfaction	5, 11, 17
Knowledge Comprehension	5, 7, 15, 16, 19, 23
Academic Achievement	5, 7, 10, 14, 16, 17
Knowledge Retention	9
Enjoyment	13, 15
Autonomy	7, 16, 20

As it is illustrated in **Table 6**, educational outcomes arising from the use of AR applications are found to be attention (1, 7, 9), engagement (3, 21), interest / interesting (3, 9, 10, 14, 22), motivation (3, 7, 16), satisfaction (5, 11, 17), knowledge comprehension (5, 7, 15, 16, 19, 23), academic achievement (5, 7, 10, 14, 16, 17), knowledge retention (9), enjoyment (13, 15), and autonomy (7, 16, 20).

What limitations are outlined regarding the use of AR applications?

Studies included into this scoping review outlined several limitations regarding the use of AR applications in formal education. The majority of the studies outlined three limitations; technical thresholds, design considerations and small sample size. **Table 7** illustrates the limitations outlined by the studies included into this scoping review.

Table 7. Limitations outlined regarding the use of AR applications

Study Number	Technical Threshold	Design Considerations	Small Sample Size
2, 5, 6, 12, 18, 20	✓		
5, 17, 18		✓	
1, 11, 13, 15, 16, 19, 20, 21, 22			✓

As it is illustrated in **Table 7**, limitations outlined regarding the use of AR applications are technical thresholds (2, 5, 6, 12, 18, 20), design considerations (5, 17, 18), and small sample size (1, 11, 13, 15, 16, 19, 20, 21, 22).

DISCUSSION AND CONCLUSION

In this section of the scoping review, findings are summarized in order to get and provide a glimpse of the current research studies on the use of AR applications in formal education. Gaps within the literature are highlighted to draw attention to the critical considerations on the development of AR enhanced learning environments.

To begin with, although there are several forms of technologies to be used in AR applications, like print-based, marker-based, location-based, gesture-based, image-based, and haptic-based, **Table 3** illustrates that the majority of the studies included into this scoping review underpinned marker-based AR technology to enhance the teaching-learning process in formal education. One of the most important reasons for the utilization of marker-based technology might be the notion of ease of use (Thornton, Ernst, & Clark, 2012). Since designing and developing high level of AR applications needs technical skills that educators might lack of (Lu, & Liu, 2015), the ones that are easily reached and used, as in the case of marker-based, might be preferred by the educators and researchers.

Second, studies included into this scoping review revealed the fact that AR applications used during the teaching-learning processes did not utilized a wide variety of pedagogical approaches. **Table 4** illustrates the pedagogical approaches that AR applications are grounded. While the situated learning approach is the one that is used most frequently, inquiry-based learning, collaborative learning, and game-based learning approaches can be seen amongst the pedagogical approaches that AR applications are integrated with. Since using AR applications within educational context is an emerging and developing phenomena (Martin-Gonzalez, Chi-Poot, & Uc-Cetina, 2015; Johnson et al., 2014; Van Arnhem, & Spiller, 2014), it might take time to integrate them with pedagogical approaches or instructional strategies. Furthermore, there might not be a guideline for integrating AR with learning theories (Santos et al., 2014), and 'a model of the factors that may maximize the use of AR for learning' (Radu, 2012).

Third, the majority of the studies included into this scoping review evaluated students' learning outcomes through learning environments in which either experimental, quasi-experimental or mixed methods research designs are used. Many of the studies, using surveys, questionnaires, open-ended statements and interviews, reported an increase in students' motivation, satisfaction, and engagement with learning environments that are enriched with AR applications. Similarly, studies that explored students' academic achievement as measured by pre-test to post-test scores reported an improvement compared to control groups, where AR applications were not used. Open-ended questions and interviews revealed students' perspectives regarding the use of AR applications in formal education. Although increasing students' motivation, satisfaction, and engagement are critical dimensions as learning outcomes, it is also important to improve students' higher order thinking skills such as problem solving, critical or creative thinking (Wang et al., 2014;) which AR applications may support as well. For instance, Wang et al. (2014) compared university students' collaborative inquiry learning behaviors and their behavior patterns in an AR and 2D simulation system. Researchers found that AR simulation is more supportive and engaged the students more thoroughly in the inquiry process. This scoping review revealed that there is a need for AR applications designed to support students' higher order thinking skills.

Fourth, the majority of the studies included into this scoping review revealed the fact that although using AR applications in formal education is valuable for desired educational outcomes, technical thresholds (Crandall et al. 2015; Lu, & Liu, 2015; Hsiao et al. 2013) are recognized amongst one of the most critical boundaries for learning effectiveness. Vaughan-Nichols (2009) stated that AR applications are spread into consumer settings more and the technology might be ready to become more commonplace. Furthermore, AR applications are becoming more attractive as a mainstream technology due primarily to the proliferation of smartphones with location-based services (Berryman, 2012). However, technical thresholds highlighted in the studies showed that there is still a gap to fulfill with respect to capabilities that AR technology serves. This gap is important since the quality of technical services affect the learning effectiveness as revealed in a research that is carried out by Tanner, Karas, & Schofield (2014). Researchers pointed out that the malfunction of the AR application might decrease the learnability of the AR enhanced animated manual, which in the end leads students to prefer static manual over AR enhanced one (Tanner, Karas, & Schofield, 2014).

Fifth, design considerations are recognized as another limitation by numerous studies. Researchers stated that ineffective design of AR applications with respect to usability considerations might lead distractions and affect the overall learning effectiveness of students. For instance Estapa, & Nadolny (2015) stated that students using the augmented document reported that there were too many items on the page, possibly leading to distraction. Chang, & Jen-ch'iang (2013) also found that the lowest satisfaction for students was the ease of use dimension, and as a result, researchers suggested that ease of use requires improvement and strengthening (Chang, & Jen-ch'iang, 2013). Kaufmann, & Dünser, (2007, p. 666) reported that students' motivation and the usability of AR applications is reduced due to the minor crashes and technical problems. However, the usability of AR applications are rated higher than the usability of a desktop application (Kaufmann, & Dünser, 2007, p. 668). It is suggested that technical issues need to be solved for improving the usability considerations even further (Kaufmann, & Dünser, 2007, p. 668)

Sixth, small sample size is one of the most important limitations that nearly each and every study had pointed out (Estapa, & Nadolny, 2015; Han et al. 2015; McMahon, Cihak, & Wright, 2015) The lack of an appropriate sample size in which AR applications are integrated with teaching-learning processes in formal education limits both educators and researchers to generalize their findings. Such a limitation might have an inhibitor effect on the construction of a conventional wisdom for the use of AR applications in formal education.

Although there is an acknowledgement that AR applications lead positive learning outcomes (Chen, & Wang, 2015; Radu, 2012), there was only three studies (11, 19, 22) focusing on the development of students' higher order thinking skills. However, the lack of or insufficient scientific evidence regarding the potential use of AR applications in supporting students' higher order thinking skills does not imply that researchers and educators should stop experimenting with those applications. Citing Goodwin, & Miller (2013, pp. 78 - 80) 'if we only implemented strategies supported by decades of research, we'd never try anything new.' There is a need for appropriate time span for both educators and researchers to provide reliable data on the use of AR applications in formal education with respect to numerous dimensions, yet the valuable query that might be made is to ask whether the use of AR applications in formal education benefits students and educators in an effective manner (Goodwin, & Miller, 2013, pp. 78 – 80; Lee, 2012, p. 20).

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