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Augmented reality as a tool to enrich educational settings

Realidad aumentada como herramienta para enriquecer los entornos educativos

MEMORIA PARA OPTAR AL GRADO DE DOCTOR

PRESENTADA POR

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AUGMENTED REALITY AS A TOOL TO ENRICH EDUCATIONAL SETTINGS

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By

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Madrid, 2020

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Memoria presentada para obtener el grado de

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Abstract

Augmented reality (AR) is an important technology that allows an interactive experience with the real world, where the objects in the real world are enhanced by computer-generated perceptual information. This information can be perceived as a natural part of the environment through different sensory modalities including visual, auditory, haptic, olfactory, and somatosensory. The term "augmented reality" was coined in 1992 and has received different definitions since then. However, a simple and broadly accepted definition describes AR as technology that overlays virtual objects over the real world. This technology has experienced a rapid growth since 2010, due in part to improvements in mobile computing power and functionality, which is reflected in the integration of AR in mobile devices such as smartphones and tablets. This technology has potential to positively influence different aspects of our daily lives. It can change the way we think, the way we entertain, the way we work, the way we communicate and, more importantly, the way we learn.

Many qualitative studies have been conducted to identify the status, trends, advantages, challenges, and opportunities of AR in education. Similarly, a significant number of quantitative studies have measured the impact of AR on education by calculating the effect size of this technology on students learning gains. However, there are still some unsolved questions about the understanding of AR and its influence on education. These questions arose from a thorough analysis of the existing literature and motivated the development of this doctoral thesis.

With this work, we aim to contribute to the understanding of AR technology as a tool to enrich educational settings. Accordingly, we first present a series of qualitative and quantitative studies that derived from the analysis of 183 empirical studies published between 2010 and 2019. These studies were intended to: 1) identify the state of the art of AR in education, 2) measure its impact on education, 3) identify the pedagogical strategies that best favor learning processes in AR interventions, and 4) recognize best practices for the development of AR applications.

Moreover, we introduce "ARtour" an AR-based educational resource whose purpose is to promote eco-agritourism, i.e., to promote agritourism while encouraging tourists to be environmentally responsible. ARtour was grounded in the theory of situated learning. Its development considered design principles identified in the existing literature and included some of the missing features identified in previous resources. From the development of ARtour and its validation in the context of a case study, we learned valuable lessons to be considered in future development of AR resources and AR interventions. These lessons could guide future research in the field of educational technology and contribute to the debate on the effectiveness of the use of information technologies to enrich teaching and learning processes.

Consequently, this thesis is composed of eight individual studies that are linked around AR and education. The studies correspond to four peer-review journal papers, three peer-review conference

proceedings papers, and one peer-review abstract. Each study is related to a specific activity that supports the main goal of identifying how AR applications can better impact educational settings. With this work, we hope to contribute to the theory and practice on the uses of AR technology to enrich education. We present evidence to students about the effectiveness of the use of AR applications as a tool to complement their learning process. We provide recommendations to teachers on how they can use AR to enhance their classes and what types of factors they need to focus on when designing AR interventions. We also provide recommendations to researchers on what directions they can take for future developments, what are the unexplored target groups, unexplored subjects, and what are the main opportunities and challenges that must be faced when dealing with AR technologies. Particularly, we offer methodological elements for the development of AR applications to enrich environmental education programs, according to our experience in the development of ARtour. Finally, we provide evidence on the effectiveness of AR on education, to encourage policymakers not only to promote the uses of this technology in education but also to guarantee the resources necessary to develop AR applications to be implemented in educational settings.

The research work leads us to conclude that AR is an important technology that seems to have taken root in educational settings. This technology has been successfully implemented in different fields of education and with different target groups. The most reported advantages are learning gains and motivation and, conversely, the most reported disadvantage is the complexity of using some educational applications. Data show that AR has a medium effect on learning outcomes; however, the results are more positive when the development of these applications considers a learning approach. Finally, the results indicate that AR applications range from basic applications that can be developed by novice developers using authoring tools, to complex applications developed by experienced programmers. The type of the application, the features included in the application, and the amount of academic content will define the cost of the application, the development time, and the resources to develop the application.

This document is divided into two parts. Part I describes the research process developed in this doctoral thesis (sections 1 to 6), while Part II presents the collection of journal papers and conference papers that resulted from the research (sections 7 to 14). Section 1 offers an overall definition of AR. Furthermore, it explains its evolution over time and describes the status of this technology in education. Section 2 presents the objectives of this thesis, while section 3 explains the research framework. Section 4 summarizes the main results of the research work. Section 5 discusses the results of the research and articulates these results to explain how they contribute to the main goal of this thesis. Section 6 presents the general conclusions of the work done in this thesis, identifies the main limitations of the research, and elucidates some indications for future investigation. Finally, sections 7 to 14 present the eight papers that were published as a result of the research work.

Keywords: Agritourism, Augmented reality, Education, Meta-analysis, Systematic review

Resumen

La realidad aumentada (RA) es tecnología que permite una experiencia interactiva con el mundo real, donde los objetos en el mundo real son aumentados por información generada por computadora. Esta información puede ser percibida como parte natural del medio ambiente a través de diferentes modalidades sensoriales que incluyen visual, auditiva, háptica, olfativa y somatosensorial. El término "realidad aumentada" fue acuñado en 1992 y ha recibido diferentes definiciones desde entonces. Sin embargo, una definición simple y ampliamente aceptada describe la RA como tecnología que superpone objetos virtuales sobre el mundo real. Esta tecnología ha experimentado un rápido crecimiento desde 2010, debido en parte a mejoras en la informática móvil, lo que se refleja en la integración de la RA en dispositivos los dispositivos móviles. La RA tiene potencial para influir positivamente en diferentes aspectos de nuestra vida diaria. Esta tecnología puede cambiar la forma en que pensamos, la forma en que nos entretenemos, la forma en que trabajamos, la forma en que nos comunicamos y principalmente, la forma en que aprendemos.

Existen varios estudios cualitativos que identifican el estado, las tendencias, las ventajas, los desafíos y las oportunidades de la RA en la educación. Del mismo modo, varios estudios cuantitativos han medido su impacto en la educación, calculando el tamaño del efecto de esta tecnología en las ganancias de aprendizaje. Sin embargo, todavía hay algunas preguntas sin resolver sobre la RA y su influencia en los entornos educativos. Estas preguntas surgieron de un análisis exhaustivo de la literatura existente y motivaron el desarrollo de esta tesis doctoral.

Con este trabajo, nuestro objetivo es contribuir a la comprensión de la tecnología de RA como herramienta para enriquecer la educación. Por consiguiente, primero presentamos una serie de estudios cualitativos y cuantitativos que se derivaron del análisis de 183 estudios empíricos. Estos estudios tenían la intención de: 1) identificar el estado del arte de la RA en la educación, 2) medir su impacto en la educación, 3) identificar las estrategias pedagógicas que mejor favorecen los procesos de aprendizaje en intervenciones de RA, y 4) reconocer las mejores prácticas para el desarrollo de aplicaciones de RA.

Además, presentamos "ARtour", un recurso educativo basado en RA cuyo propósito es promover el agroturismo ecológico, es decir, promover el agroturismo y alentar a los turistas a ser responsables con el medio ambiente. ARtour se basó en la teoría del aprendizaje situado y su desarrollo incluyó algunas de las características faltantes en recursos anteriores. Del desarrollo de ARtour y su posterior validación, aprendimos lecciones a ser consideradas en el desarrollo de recursos e intervenciones de RA. Estas lecciones podrían guiar la investigación futura en el campo de la tecnología educativa y contribuir al debate sobre la efectividad del uso de las tecnologías de la información para enriquecer los procesos de enseñanza y aprendizaje.

En consecuencia, esta tesis se compone de varios estudios que están vinculados en torno a la RA y la educación. Los productos presentados en esta tesis corresponden a cuatro artículos de revistas

indexadas; tres artículos de conferencias; y un resumen de conferencia. Cada estudio corresponde a una actividad específica que apoya al objetivo principal de identificar cómo las aplicaciones de RA pueden tener un mejor impacto entornos educativos. Con este trabajo, esperamos contribuir a la teoría y práctica sobre los usos de la tecnología de RA para enriquecer los entornos educativos. Proporcionamos recomendaciones a los maestros sobre cómo pueden usar la RA para mejorar sus clases y en qué tipos de factores deben enfocarse al diseñar intervenciones de RA. También brindamos recomendaciones a los investigadores sobre las direcciones que pueden tomar para desarrollos futuros, cuáles son los grupos inexplorados, los campos educativos inexplorados y cuáles son las principales oportunidades y desafíos que deben enfrentarse cuando se trata de tecnologías de RA. Finalmente, brindamos evidencia sobre la efectividad de la RA en la educación, para alentar a los interesados no solo a promover el uso de esta tecnología en la educación, sino también para garantizar los recursos necesarios para desarrollar aplicaciones de RA que se implementen en entornos educativos.

El trabajo de investigación nos lleva a concluir que la RA es una tecnología importante que parece haberse arraigado en entornos educativos. Esta tecnología se ha implementado con éxito en diferentes campos de la educación y con diferentes grupos objetivo. Las ventajas más reportadas son las ganancias de aprendizaje y la motivación y, por el contrario, la desventaja más reportada es la complejidad del uso de algunas aplicaciones educativas. Los datos muestran que la RA tiene un efecto medio en las ganancias de aprendizaje de los estudiantes; sin embargo, los resultados son más positivos cuando el desarrollo de estas aplicaciones considera un enfoque de aprendizaje. Finalmente, los resultados indican que las aplicaciones de RA van desde aplicaciones básicas que pueden ser desarrolladas por desarrolladores novatos utilizando herramientas de autor, hasta aplicaciones complejas desarrolladas por programadores experimentados. El tipo de aplicación, las características incluidas en la aplicación y la cantidad de contenido académico definirán el costo de la aplicación, el tiempo de desarrollo y los recursos para desarrollar la aplicación.

Este documento está dividido en dos partes. La Parte I describe el proceso de investigación de esta tesis doctoral (secciones 1 a 6), mientras que la Parte II presenta la colección de artículos de revistas y conferencias que resultaron de la investigación (secciones 7 a 14). La sección 1 ofrece una definición general de la RA. Además, explica su evolución a lo largo del tiempo y describe el estado de esta tecnología en la educación. La sección 2 presenta los objetivos de esta tesis, mientras que la sección 3 explica la metodología. La sección 4 resume los principales resultados de la investigación. La sección 5 discute los resultados y los articula para explicar cómo contribuyen al objetivo principal de esta tesis. La sección 6 presenta las conclusiones generales del trabajo realizado, identifica las principales limitaciones, y aclara algunas indicaciones para futuras investigaciones. Finalmente, las secciones 7 a 14 presentan los 8 artículos que resultaron del proceso de investigación.

Palabras clave: Agroturismo, Educación, Metaanálisis, Realidad aumentada, Revisión sistemática

PART I

DESCRIPTION OF THE RESEARCH

This part of the document first describes the theoretical background of AR and the implications of this technology in education. Then, it defines the main objectives of the thesis and describes the activities carried out to achieve each objective. Subsequently, it explains the main findings of the research work and clarifies the implications of these results for education. Finally, it presents the general conclusions of the thesis and the implications for future research.

1. Introduction

1.1 The role of technology in education

The role of technology in learning is probably the most familiar and lasting debates in the field of instructional technology (Sickel, 2019). This has been a point of discussion for decades and has been broadly known as the Clark/Kozma debate, so named for its key disputants. This debate focuses on the role of technology in the learning process and presents two opposing points of view. On the one hand, Clark (1994) declared that technology, or any other media, has no influence on learning per se. He argued that technology is just a conduit through which instruction is delivered, and it is the pedagogical strategy the only responsible for achieving the purpose of learning. On the other hand, Kozma (1994) declared that media enables and restrict the method and the methods are based on the capabilities of the media. He highlighted that technology offers unique attributes that enhance the learning process, which enables the delivery of contents that could not be adequately relay via traditional instruction. This debate will continue and perhaps will never be resolved. However, we assert that, regardless of one's pedagogical preferences or philosophical perspective, it is critical to consider methods along with media in research and in practice.

Supporting Kozma's position that technology offers unique attributes that enhance the learning process, many studies have been conducted to demonstrate the advantages, disadvantages, opportunities, and challenges of technology in education (Chauhan, 2016; Fu, 2013; Hsu, Hung, & Ching, 2013; Laurillard, 2002; Martin et al., 2011; Zhou & Purushothaman, 2019). One of the most outstanding possibilities of technology, and in particular, of information technologies, is that it enhances active learning methodologies (Michael, 2006; Su & Cheng, 2015; Zhou & Purushothaman, 2019).

Active learning is often presented as a radical change from traditional instruction and is defined as an instructional method that involves students in the learning process. In summary, active learning fosters students to engage in meaningful learning activities and reflect on what they are doing (Bonwell & Eison, 1991). Several studies demonstrate that active learning methodologies enrich students' experience, favors learning gains, and promote values such as responsibility, motivation, enjoyment, autonomy, among others (Michael, 2006). In this sense, one of the technologies that better promotes active learning is augmented reality (Garzón, Pavón, & Baldiris, 2019). This technology enriches education by transforming passive learning materials into interactive learning experiences, which is reflected in students learning gains, increased motivation to learn, and many other benefits.

1.2 Augmented Reality

Augmented Reality (AR) is a technology that makes use of multimedia tools to improve the experience of interacting with reality. This technology has been studied and developed since the early 1960s along with the emergence of Virtual Reality (VR). Sometimes these two technologies are confused with each other, but while VR immerses the user in a totally virtual environment, AR is rather a combination of virtuality and reality.

The first AR system is attributed to cinematographer Morton Heilig, who in 1962 created “Sensorama”, a multisensory technology that provided a visual, sound, vibration, and odor sensory experience (Carmigniani et al., 2011). Later, in 1968 computer scientist Ivan Sutherland invented the “Sword of Damocles”, which is considered to be the first head-mounted display system (Krevelen & Poelman, 2010). Then, in 1975 Myron Krueger creates the “VIDEOPLACE”, the first system that allowed users to interact with virtual objects in a real-time application (Krueger, Gionfriddo, & Hinrichsen, 1985).

Caudell and Mizell (1992) coined the term “Augmented Reality” to describe the technology that allows a computer-produced diagram to be superimposed on a real-world object. Subsequently, the first formal definition of AR was presented by Azuma (1997) as a technology that allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. However, this definition has evolved considering that AR can be experienced with all the senses and not only with the sense of sight. In this way, Akçayir & Akçayir (2017) proposed a simple, accurate, and wide definition of AR as a technology that overlays virtual objects into the real world.

Prior to 2010, most AR applications were complex and expensive systems that were difficult to access because of their high costs and limited expansion. Nevertheless, improvements in mobile computing power and functionality, led to the integration of AR systems into mobile devices making this technology available to a greater number of users (Mekni & Lemieux, 2014). This integration has led to an accelerated increase in AR applications, which have been successfully implemented in many areas such as industry, medicine, tourism, and education (Akçayir & Akçayir, 2017; Garzón, Acevedo, Pavón, & Baldiris, 2018; Ha & Hong, 2016; Yim, Chu, & Sauer, 2017).

Experts predict that in the near future, AR will be the new computing platform and current screen machines will be replaced by immersive devices based on AR (Qiao et al., 2019). In this sense, stand-alone headsets such as HoloLens, Oculus Rift, or the upcoming iGlass form part of a new generation of devices that will create a renewed paradigm for AR. Although AR has already become one of the most interesting technologies in the digital industry, experts assure that AR has not reached its full potential. Future developments such as the Augmented Reality-based Web (WebAR) or the integration of AR with artificial intelligence and machine learning will bring unthinkable applications. In short, AR has a great potential to change the way we think, the way we entertain, the way we communicate, and more importantly, the way we learn.

1.3 Augmented reality in education

The first AR system exclusively designed to be implemented in education was a tool for visualizing dynamic 3-D anatomy. This AR tool superimposed and registered bone structures on real anatomical counterparts of a human subject to teach anatomy using a head-mounted display. The system was created at the University of North Carolina and introduced by its creators in the first International Conference on Computer Vision, Virtual Reality, and Robotics in Medicine held in Nice France in 1995 (Kancherla, Rolland, Wright, & Burdea, 1995). There is an important number of applications that followed the dynamic 3-D anatomy visualizer. The study by Chang, Morreale, and Medicherla (2010) analyzed the influence of AR on education during the period from 1995 to 2010 describing its affordances and potential to improve education. The study highlights applications in medicine, engineering, and natural sciences and proposes possible routes for future research. However, as mentioned before, the high cost of this technology before 2010 made it difficult to implement in educational settings, and therefore only a few educational institutions could afford AR systems. Most of these systems consisted of head-mounted displays for viewing virtual 3D objects in the real-world environment, thereby limiting the augmentation to the sense of sight.

Conversely, as a positive consequence of the integration of AR into mobile devices, the last decade has experienced a significant increase of AR applications for education (Akçayir & Akçayir, 2017; Garzón & Acevedo, 2019). These applications cover diverse target groups and different fields of education, helping students develop special skills that are much more difficult to obtain with other pedagogical resources (Cheng & Tsai, 2016). For example, AR permits learners to access unobservable phenomena such as the behavior of magnetic fields (Ibáñez, Di Serio, Villarán, & Delgado Kloos, 2014) or the easy understanding of architectural blueprints (Portman, Natapov, & Fisher-Gewirtzman, 2015), among others, which have been identified by teachers and previous research as troublesome for students.

From the analysis of the background of AR in education, Garzón (in press) define three generations of AR in education (see Figure 1). The first generation covers the period between 1995 and 2009, the second generation from 2010 to 2019, and the third generation from 2020 onwards. The first generation is characterized by expensive and complex AR systems based on devices such as handheld displays, head-mounted displays, and heads-up displays. Most of these systems were intended to teach subjects related to health, biology, civil engineering, and geometry and focused on bachelor students as target groups. The second generation is characterized by mobile AR applications, based in most cases, on smartphones and tablets. Most of these systems are intended to teach subjects related to natural sciences, mathematics, engineering, and arts and focused on primary, secondary, and bachelor education. Finally, the third generation is expected to be characterized not only by mobile AR but also by WebAr-based applications and stand-alone headsets. Similarly, future AR applications are expected to cover all subjects and target groups, but more importantly, AR applications are expected to be accessible to any person despite their special needs or preferences.

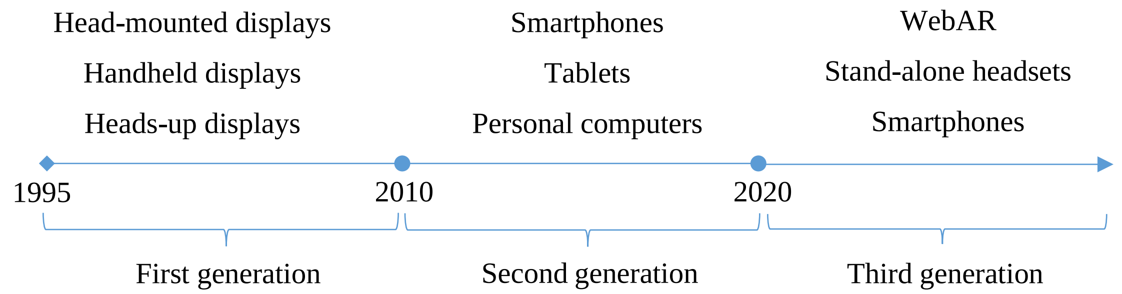

Figure 1. Generations of AR in education.

Since the first appearance of AR in education, many studies have been conducted to identify the status, tendencies, advantages, opportunities, and challenges of these technology in educational settings. Billinghurst (2002) published perhaps the first analysis of AR in education. This analysis described AR as an especially valuable technology for education as it can support seamless interaction between real and virtual environments and holds the ability to transition smoothly between reality and virtuality. However, the limited number of available user studies, did not allow it to identify the real impact of AR on education. The evolution of AR, as well as its affordances and limitations in education, were described by Dunleavy, Dede, and Mitchell (2009) in a study that has been considered to be the first analysis of users' studies. Finally, the study by Yuen, Yaoyuneyong, and Johnson (2011) may be considered the limit between the first and second generations of AR in education. This study stated that AR has substantial potential implications and numerous benefits for teaching and learning. Based on the analysis of previous research, they proposed five educational applications of AR technology: AR books, AR gaming, discovery-based learning, objects modeling, and skills training. The study posed, accurately, that such directions would guide the future of AR in education.

The second generation of AR in education begins with a significant increase in the number of AR applications for education, most of them based on mobile AR. Consequently, many systematic reviews have been carried out since then. Table 1 and Table 2 present a general summary of the most cited literature review studies that were conducted before this doctoral thesis. Table 1 presents some of the more important findings in eight qualitative literature review studies. These literature reviews summarize the results of more than 305* individual studies of AR applications for education from 2003 to 2018. Similarly, Table 2 presents the main findings of four quantitative reviews, particularly meta-analyses, that have been conducted to analyze the influence of AR on education. These meta-analyses used standard deviations, mean scores, and sample sizes reported in the studies to calculate Cohen's *d* effect size (Cohen, 1992). Further, these studies analyzed moderator variables to provide a complete information regarding AR in education.

* The studies by Wu et al. (2013) and Cabero Almenara & Barroso Osuna (2016) did not provide the number of studies included in the analysis.

Table 1. Qualitative reviews of AR for education prior to this doctoral thesis.

Study	Analyzed variables	Main findings
(Carmigniani et al., 2011)	Computer vision methods; AR interfaces; AR applications	AR brings the possibility of enhancing missing senses. AR has been socially accepted thanks to its integration into mobile devices. AR expands people's skills and senses.
(Radu, 2012)	Learning effects; advantages; disadvantages	AR increases content understanding. AR favors long-term knowledge retention. AR increases learning motivation.
(Wu et al., 2013)	Features and affordances; learning effects; technological issues; pedagogical issues; learning issues	AR can enable: - learning content in 3D perspectives, - ubiquitous, collaborative and situated learning, - learners' senses of presence, immediacy, and immersion, - visualizing the invisible.
(Bacca, Baldiris, Fabregat, Graf, & Kinshuk, 2014)	Trends of AR in education; advantages and disadvantages; field of education, level of education	The number of AR studies have incremented since 2010. The main advantages of AR in education are learning gains and motivation. The main difficulty is maintaining superimposed information. Very few systems have considered the special needs of students in AR.
(Diegmann, Schmidt-Kraepelin, Eynden, & Basten, 2015)	Benefits of AR in education	AR favors content understanding, language Association, and physical task performance.
(Cabero-Almenara & Barroso-Osuna, 2016)	AR applications	The integration of AR into teaching implies several principles such as: designing environments; working with curricular contents and enabling teachers to acquire digital skills.
(Akçayir & Akçayir, 2017)	Advantages and disadvantages; field of education, level of education	The most reported advantage of AR is that it promotes enhanced learning achievement. The most reported challenge is the difficulty for students to use it.
(Sirakaya & Sirakaya, 2018)	Trends of AR in education; field of education; level of education, type of augmentation	Most common target group is undergraduate students. Most common subject Natural Sciences. Most AR applications are marker-based

Table 2. Summary of the meta-analyses of AR in education prior to this doctoral thesis.

Author	N	d	Moderator analysis
(Santos et al., 2014)	7	.56	Display device, software libraries.
(Tekedere & Göker, 2016)	15	.67	Grade level, field of education.
(Yilmaz & Batdi, 2016)	12	.36	Cognitive domain.
(Ozdemir, Sahin, Arcagok, & Demir, 2018)	16	.51	Grade level, display device, sample size.

1.4 Previous related work

In this subsection, we expand the information on the studies shown in Table 1 and Table 2. We differentiate qualitative studies from quantitative studies in order to gain a clearer knowledge of the state of the art of AR in education. First, we analyze eight systematic literature reviews published between 2011 and 2018, and then, we examine four quantitative meta-analyses published between 2014 and 2018.

1.4.1 Previous systematic literature reviews

The first systematic literature review of AR in education was published by Carmigniani et al. (2011). The review analyzed 25 studies published between 2002 and 2010 in order to describe the most important applications of AR in education. This study stated that the impact of AR on education is low compared to other technologies. However, this technology is in its infancy and the evolution of AR to mobile AR is a successful megatrend that will potentially play a very important role in education in the near future. The study highlighted that AR was socially accepted thanks to its integration into mobile devices, expanding people's skills and senses beyond the sense of sight.

Radu (2012) published a systematic literature review of 32 individual studies, most of them belonging to the first generation of AR in education. The review compares the learning effects of AR versus non-AR applications. It also highlights the effectiveness of AR systems to teach spatial structures such as geometrical shapes, chemical structure, or astronomy configurations. Similarly, the study emphasizes the effects of AR on long-term memory retention, potentially benefiting subjects related to language learning, among others. More importantly, this study was the first to annotate that one of the most significant benefits of AR for education is that it increases students' motivation to learn. Conversely, as negative effects, the study reports that AR systems demand more attention from the students, which could cause students to ignore important parts of the instruction.

The study by Wu et al. (2013) established the state of the art of AR in education as for 2013. The study identified features and affordances of AR in education and posed some directions for future research. It assures that the success of instruction through AR systems relies not only on the technology but also on the instructional approach adopted. It also points to cognitive overload as the main challenge to be faced when using AR applications in education and claims the need to consider larger samples and longitudinal studies. Finally, the authors conclude that AR is still in its initial stage, and therefore, it is shaded by other more mature technologies in education.

Bacca et al. (2014) analyzed 32 studies published between 2003 and 2013 to identify the trends of AR in education. The study identified that most AR applications to date were aimed at teaching subjects related to natural sciences and that the most common target group was Bachelor education. As for the advantages of using AR in education, the study found that the most reported advantages were learning gains and motivation. Conversely, the lack of inclusive applications that consider the special needs and preferences of users is the main challenge of this technology for education. Finally, the authors highlight the need to develop AR applications to teach subjects related to unexplored fields of education such as agriculture, forestry, and fisheries.

Diegmann et al. (2015) conducted a systematic literature review of 25 empirical studies to identify the benefits of AR in educational environments. Based on the five directions by Yuen et al. (2011) the authors classified the studies to detail possible benefits for different directions of AR applications. The study found that the most reported benefit was increased motivation, referring to students being more eager, interested, and engaged compared to non-AR applications. It also highlights increased attention, increased concentration, and increased satisfaction. Finally, the authors point that using AR applications reduces costs compared to traditional non-AR learning tools.

Cabero-Almenara and Barroso-Osuna (2016) described the educational possibilities of AR. The study confirms that AR applications have been successfully implemented with different target groups to teach various fields of education, indicating that this is a suitable technology to be included in educational settings. Nevertheless, the study emphasizes that the incorporation of AR in education, must not imply a technological problem but rather a didactic issue. In this sense, the study proposes that AR research must include the identification of which pedagogical strategies best benefit each educational context. Thus, the authors highlight the need for a two-way strategy: training teachers to use AR technology and integrating pedagogical strategies in the implementation of AR technologies.

Perhaps the most important contribution of the study by Akçayir and Akçayir (2017) is its broad definition of the term “augmented reality”. They define AR as a technology that overlays virtual objects into the real world. This definition has three important characteristics: 1) it is accurate 2, it is simple, and 3) it does not limit AR to the sense of sight. The study analyzed 68 empirical studies published between 2007 and 2015 to identify the advantages and challenges associated with AR for education. It highlights learning gains and motivation as the main advantages of AR in education, whereas the most important challenge to be solved is the development of design principles that includes guidance on the pedagogical strategies that must accompany AR interventions.

As far as we know, the study by Sirakaya and Sirakaya (2018) was the last systematic literature review performed before this doctoral thesis. The study analyzed 105 empirical studies published between 2011 and 2016 to identify the trends of AR in education. It found that 2013 was the year of the biggest increment on the number of AR on education. The authors justify this increase by the enhanced role of mobile devices in education, which also explains the fact that AR applications for education have reduced their costs compared to traditional AR systems based on head-mounted displays, handheld displays, or heads-up displays. Finally, the study suggests the need to include students with special needs as target public for AR applications.

1.4.2 Previous meta-analyses

To our knowledge, four quantitative meta-analyses that measured the impact of AR on education were performed before this doctoral thesis (see Table 2). The concept of Meta-analysis is defined as “the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating findings” (Glass, 1976, p. 3). Meta-analyses are an alternative to qualitative reviews that proceed from particular observations to general statements (Garzón & Acevedo, 2019). The particular observations allow measuring the effect size of an intervention, which represents the magnitude of the experimental effect. Subsequently, the calculation of an overall effect size represents the effect of a group of individual studies and allows establishing general statements about the impact of a particular treatment. Meta-analyses combine relative samples and effect sizes from different studies; therefore, the overall result is more precise because of the magnitude of the analysis. In addition, meta-analyses focus on comparison studies versus one-shot studies which allows control of internal validity (Bernard et al., 2004). In summary, meta-analyses are more objective and less judgmental than literature reviews.

Santos et al. (2014) conducted the first meta-analysis of the impact of AR on education. The study analyzed 7 empirical studies published between 2009 and 2012 and found an overall effect size of 0.56, concluding that AR has a medium impact on education according to Cohen’s classification (1992). The second meta-analysis of the impact of AR on education was conducted by Tekedere & Göker (2016). The study analyzed 15 studies published between 2010 and 2015 and found an overall effect size of 0.56, also concluding, that AR has a medium impact on education. Yilmaz and Batdi (2016) conducted the third meta-analysis of the impact of AR on education. The meta-analysis included 12 empirical studies and found an overall effect size of 0.34 that corresponds to a small effect. It is important to clarify that this is the only meta-analysis that conclude that AR has a small impact on education. Finally, the fourth meta-analysis of the impact of AR on education was conducted by Ozdemir et al. (2018). The meta-analysis included 16 empirical studies published between 2007 and 2017 and found an overall effect size of 0.51 that corresponds to a medium impact on education.

These four meta-analyses represent the first studies measuring the impact of AR on education and guided research regarding the best practices for developing AR applications. However, these meta-analyses have five important limitations. First, they do not standardize the findings of studies with different research designs for direct comparison. Second, the sample in each meta-analysis is relatively small, which risk producing random noise and publication bias. Third, these meta-analyses do not perform moderator analyses to assess the variables that may influence the impact of AR on education. Four, these meta-analyses do not analyze the impact of AR according to the type of student or the field of education. Fifth, these meta-analyses do not analyze the characteristics of AR treatments, in order to inform teachers, and researchers, what educational contexts best benefit AR interventions.

1.5 Research gaps of AR in education

The thorough analysis of the findings in the previous qualitative and quantitative studies led us to identify some research gaps regarding the uses of AR applications in education. First, the literature regarding the status of AR in education needs to be updated, to establish what characteristics differentiate this technology from others. This allows us to identify what is the unique value of AR-based learning environments, which leads to establishing possible routes for future research.

Second, although some quantitative studies attempted to measure the effect size of AR on education, their small number of analyzed studies led them to some limitations. To start with, they do not standardize the findings of studies with different research designs for direct comparison, which yields a small number of meta-analyzed studies (Carlsbon & Schmidt, 1999). Consequently, meta-analyses with small samples are more likely to suffer from random noise and publication bias (Gurevitch, Koricheva, Nakagawa, & Stewart, 2018). Finally, such a small sample in these meta-analyses does not allow them to accurately perform moderator analyses to assess the variables that may influence the impact of AR on education. In addition, it has been repeatedly pointed out that only a few AR applications address the special needs of users (e.g. people with disabilities), which supposes a step back in terms of social inclusion. However, although there is a claim for the inclusion of accessibility characteristics to address the special needs of users, no study has been conducted to identify the impact of AR on the learning gains of students with special needs. That is, no data show that using this technology benefits the learning process of students with special needs or under what conditions AR should be used to complement their education.

Third, most of the previous studies failed to analyze the pedagogical approaches that accompany each AR intervention, somehow ignoring that the success of an intervention depends not only on the technical characteristics of the technology but also on the pedagogical strategies to implement them. Different studies have indicated that the lack of instructional approaches when applying AR to learning activities tends to confuse and frustrate students (Chen, Chou, & Huang, 2016; Chu, Hwang, & Tsai, 2010). Consequently, the analysis of the integration of different pedagogical strategies in AR interventions is a pending issue in AR literature.

Fourth, despite their technical efficiency, many AR applications lack explicit learning purposes. That is, these applications are designed by experimental programmers and consequently their quality in terms of technology is appropriate. However, some of these applications lack instructional methodologies, which constitute the core of the success of educational processes (Khalil & Elkhider, 2016; Liu & Chu, 2010). Instructional methodologies translate the general principles of learning to provide a procedural framework for developing effective pedagogical material that yields successful learning outcomes. In consequence, it is important to establish design principles based on instructional methodologies, to guide the development of AR applications that are pedagogically accurate and technically efficient.

2. Objectives

The main goal of this thesis is to contribute to the understanding of AR technology as a tool to enrich educational settings. Based on the aforementioned research gaps, we defined the objectives to be pursued in this doctoral thesis and the activities that must be performed to achieve each objective. With this, we hope to push the limits of the knowledge of the field, establishing the trends, status, advantages, challenges, and opportunities of AR applications for education. We aim to provide indications for theory and practice to help students, teachers, researchers, and policymakers make the most of this technology to improve teaching and learning processes. We defined four specific objectives whose fulfillment would lead us to achieve our main goal. Next, we describe each specific objective and list the manuscripts that derive from each objective.

2.1 Status and tendencies in the usage of AR in education

The first specific objective defined a set of research questions to be investigated to establish the status and tendencies in the usage of AR in education. We conducted a systematic literature review to comply with this objective. The purpose of the review was to establish the state of the art of AR in education and identify the trends, advantages, challenges, and opportunities of AR in education. As a result of the work done on this objective, we wrote two manuscripts: 1) "Systematic review and meta-analysis of augmented reality in educational settings" (section 7) (Garzón, Pavón, & Baldiris, 2019) and 2) "Augmented Reality Applications for Education: Five Directions for Future Research" (section 8) (Garzón, Pavón, & Baldiris, 2017).

2.2 Impact of AR on education

The second specific objective sought to identify the impact of AR applications on education. We carried out a meta-analysis of a set of empirical studies, to investigate the impact of AR on students' learning gains. Furthermore, the study analyzed the influence of variables such as control treatment, learner type, and domain subject on students' learning gains. Additionally, we performed a meta-analysis to identify the impact of AR on the learning gains of students with special needs. As a result of the work done on this objective, we wrote the manuscripts: 1) "Meta-analysis of the impact of Augmented Reality on students' learning effectiveness" (section 9) (Garzón & Acevedo, 2019) and 2) "Meta-analysis on the Impact of Augmented Reality on the Learning Gains of Students with Special Needs" (section 10) (Garzón, Baldiris, & Pavón, 2019).

2.3 Pedagogical strategies of AR interventions

The third specific objective aimed at identifying the pedagogical strategies of AR interventions that best favor students' learning gains. This objective included a meta-analysis whose purpose was to identify, in the light of the learning theories, how learning methods affect the impact of AR on education. In addition, the study analyzed the effect of moderating variables such as learning environment and intervention duration. As a result of the work done on this objective, we wrote the manuscript: "How do pedagogical approaches affect the impact of augmented reality on education? A meta-analysis and research synthesis" (section 11) (Garzón, Kinshuk, Baldiris, Gutiérrez, & Pavón, 2020).

2.4 Design principles to develop AR educational applications

Finally, the fourth specific objective was based on the findings of the three specific objectives above. It aimed at proposing a set of design principles to guide the development of AR educational applications. Further, it provides ideas on the design of AR interventions that accurately implement the AR educational applications. The design principles were validated through the development of an AR-based educational resource to promote eco-agritourism, that is, to promote agritourism while encouraging tourists to be environmentally responsible. In addition, we designed an educational intervention to validate the efficacy of the resource as a pedagogical tool to enrich educational settings. The pedagogical characteristics of the intervention respond to the findings of our studies regarding time, pedagogical approach, and learning environment to validate in practice, our theoretical findings.

The process of development and the subsequent validation of the educational resource left us valuable methodological lessons. We pose that these lessons could guide future research regarding the development of AR applications and AR interventions to continue enriching the teaching and learning processes. As a result of the work done on this objective, we wrote three manuscripts: 1) "ARtour: Augmented reality-based game to promote agritourism" (section 12) (Garzón, Acevedo, Pavón, & Baldiris, 2018), 2) "Augmented Reality-based application to foster sustainable agriculture in the context of aquaponics" (section 13) (Garzón, Baldiris, Acevedo, & Pavón, 2020), and 3) "Promoting eco-agritourism using an augmented reality-based educational resource: a case study of aquaponics educational resource: a case study of aquaponics" (section 14) (Garzón, Acevedo, Pavón, & Baldiris, 2020).

3. Research framework

This thesis adopted a mixed approach that involved three stages, first a systematic literature review, second, the establishment of a set of design principles, and finally, the design of an AR-based educational application. The literature review aimed at achieving the first, second, and third research objectives. The set of design principles are based on the results of the literature review and refers to the fourth research objective. Finally, the development process and subsequent validation of the AR-based educational application empirically supports the results of the four research objectives.

3.1 Systematic literature review

The purpose of the literature review was to identify the state of the art of AR in education. This stage was divided into two main activities, namely a qualitative literature review and a quantitative literature review. The qualitative literature review aimed at identifying the trends, advantages, challenges, and opportunities of AR in education as stated in our first research objective. Likewise, the quantitative literature review aimed at measuring the impact of AR on education as stated in our second and third research objectives.

3.1.1 Qualitative review

The qualitative literature review followed the guidelines proposed by Kitchenham and Charters (2007), who suggest that systematic reviews involve three main stages: planning, conducting, and reporting the review. We used the Web of Science (WoS) site to search for relevant literature to answer the research questions in the first objective. This search resulted in 61 empirical studies published between 2012 and 2018 in scientific journals and conference proceedings. The research questions and the search protocol including the selection of the studies, the eligibility criteria, and the data coding process is explained in section 7. The results of this qualitative review were published in two research papers. First, a study that established the status and trends in the use of AR in education (Garzón, Pavón, et al., 2019) and second, a study that established five directions for future research in the area of educational AR (Garzón, Pavón, & Baldiris, 2017).

3.1.2 Quantitative review

The quantitative literature review was performed in the context of a meta-analysis conducted in accordance with the PRISMA guidelines (Moher, Liberati, Tetzlaff, & Altman, 2009). The purpose of the meta-analysis was to collect, assess, and summarize empirical evidence to measure the impact of AR on education. Sixty-four quantitative studies from Web of Science, Scopus, and Google Scholar were selected for the analysis. The search protocol including the selection of the studies, the eligibility criteria, and the data coding process is explained in section 9. The results of this quantitative review were published in three different research papers. First, a study that measures the overall effect size of AR on education (Garzón & Acevedo, 2019), second, a study that measures the effect size of AR on special needs education (Garzón, Baldiris, et al., 2019), and third, a study that identifies how do pedagogical approaches affect the impact of AR in education (Garzón, Kinshuk, et al., 2020).

3.2 Design principles

These principles are based on the results of the qualitative and quantitative literature reviews and refer to good practices in the design of AR experiences. We differentiate two types of principles, first, principles to develop AR applications and second, principles for performing AR interventions.

3.2.1 Design of AR applications

To establish the principles for designing AR applications, we built on the challenges encountered in previous AR applications. The study by Garzón, Baldiris, et al. (2019), product of our first research objective, identified the most relevant disadvantages and challenges of AR in education. The results indicated that the most reported disadvantages are the complexity of using AR applications and the cognitive load that the use of these applications can cause. Consequently, we established two principles related first, with the use of Instructional Design Models (IDM) and second, with how to improve AR applications' usability. Similarly, the study identified accessibility barriers as a major challenge of AR in education. Consequently, our third principle refers to how to design applications that can be used by anyone, regardless of their special needs or preferences. Finally, another important challenge is related to the low dissemination of AR applications. Some authors signal this issue because of the lack of programming abilities of potential developers such as teachers or inexperienced researchers. Hence, the fourth principle presents a series of software tools that stakeholders can use to develop AR applications. This principle includes tools for professional programmers who do not have experience developing AR applications and instructions for inexperienced developers, by using authoring tools.

3.2.2 Design of AR interventions

To establish the principles for designing AR interventions, we built on the results of our third research objective. The study by Garzón, Kinshuk, et al. (2020) analyzed the pedagogical characteristics that best favor AR interventions considering the levels of education and the fields of education. The study focused on different approaches from the constructivist theory that have accompanied the validation of AR applications. Additionally, the study analyzed the learning environment and the intervention duration as moderator variables of the impact of AR on education. Consequently, the principles for designing AR interventions inform stakeholders about the best pedagogical strategies to implement in each specific scenario.

3.3 AR-based educational application

This stage is based on the results of the four research objectives and empirically supports the proposed design principles. The stage comprises two processes, first the development of an AR-based educational application and second, the validation of the application in the context of a case study.

3.3.1 Development of the application

We designed an educational AR application to promote agritourism in the context of aquaponics. The application, ARtour, was developed following the proposed principles regarding instructional design, usability, accessibility, and software.

As proposed in the first design principle, the development of ARtour followed the guidelines of an IDM. Its development included five stages namely, analysis, design, development, implementation, and evaluation. Using this procedure allowed us to maximize the software creation process and translate the learning principles into an effective pedagogical application. The usability of the application was addressed following a user-centered design approach seeking to understand the target users' needs and preferences. Consequently, we considered elements related to User-information, User-cognitive, User-support, User-interaction, and User-usage. This procedure allowed us to lower the complexity of using the application, which somehow means improving the user's experience. Similarly, the accessibility of ARtour was addressed by including elements related to perceptibility, operability, understandability, and robustness. Including these elements ensures that more people, regardless of their special needs or preferences, can use the application on their own without further assistance. Finally, as suggested in our fourth design principle, the application was developed using software tools including Unity 3D, Vuforia, Inscape, and Blender. The use of these tools allowed us to develop a free and efficient application that aims to promote eco-agritourism in the form of aquaponics.

3.3.2 Validation of the application

The validation of the application was held in the context of a case study following the appropriate pedagogical strategies as stablished in our third research objective (see section 14). The purpose of the case study was to validate the effectiveness of ARtour as a pedagogical tool to promote agritourism. The study was held in an aquaponic system located in an agritourism fam in northwestern Colombia and involved 40 vocational education students. The intervention included the proposed insights to design AR interventions regarding pedagogical approach, learning environment, and interventions duration. In addition, the process allowed to measure variables such as learning gains, knowledge retention, and motivation, with positive results that indicate the feasibility of using ARtour as a pedagogical tool. Figure 2 elucidates the research framework. The blue boxes indicate the three stages of the research process, the pink boxes indicate the sub-stages, and the grey boxes the research papers.

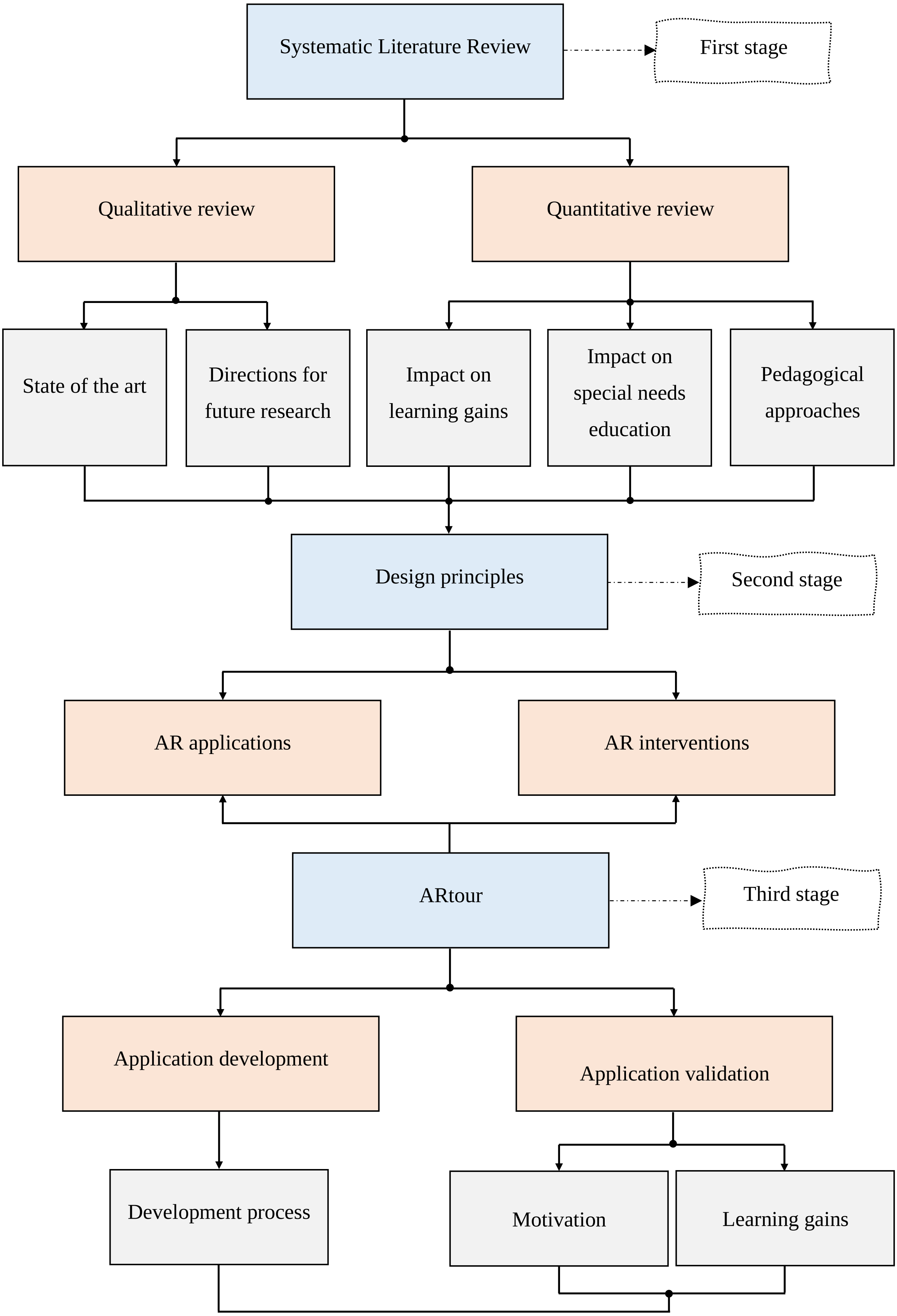

Figure 2. Research process flow chart.

4.Results

This section describes the main results of the thesis, according to the four objectives that were previously defined. First, we describe the status and tendencies in the use of AR in education. Second, we aim at identifying the impact of AR on education and the variables that moderate this impact. Third, we identify the pedagogical strategies that best benefit education, and fourth, we propose a set of design principles to guide the development of AR applications.

4.1 Status and tendencies in the usage of AR in education

To identify the status and tendencies of AR in education we considered five aspects. First, the evolution over time regarding the number of publications in scientific journals. Second, the levels of education in which AR is most applied and the impact of AR on student's learning gains in each level of education. Third, the fields of education in which AR is most applied and the impact of AR on student's learning gains in each field of education. Fourth, the advantages of using AR in education, and fifth, the disadvantages of using AR in education. The main results of the work performed to achieve this objective were published in the systematic literature review shown in section 7 and in the study shown in section 8. In this subsection, we synthesize some of the most significant results.

4.1.1 Evolution over time of AR in education

To identify the evolution over time of AR applications for education, we performed a search in the Web of Science core collection, as it is considered the most important bibliometric database (Mongeon & Paul-Hus, 2016). We searched for the term *Augmented Reality in education* and found 2047 studies published between 1996 and 2019.

Figure 3 presents the evolution in the number of studies related to AR in education, including books, book chapters, articles, and proceeding papers. Figure 4 presents the list of the most influential authors according to the number of published studies and Figure 5 sort the list by country of the authors. Finally, Figure 6 presents the number of studies of AR in education according to the universities or institutions were the research was conducted.

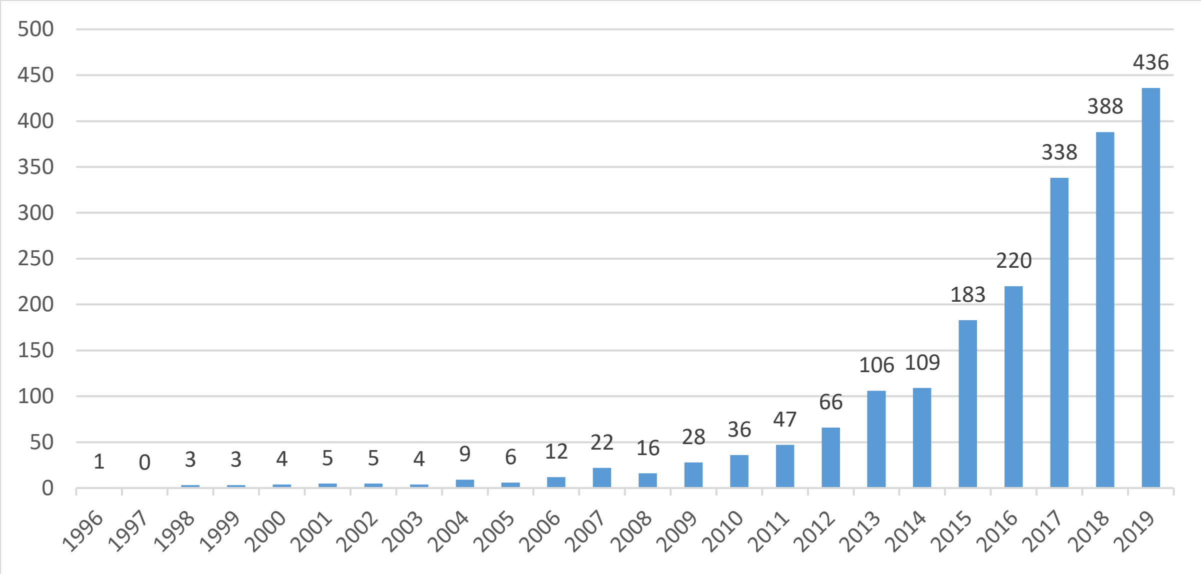

Figure 3. Number of studies of AR in education per year.

Figure 3 shows the increase in the number of studies related to AR in education from 1996 to 2019. We highlight that this increase is more notorious since 2010, that is, since the beginning of the first generation of AR in education. We do not include studies published in 2020, as these data were collected May 15.

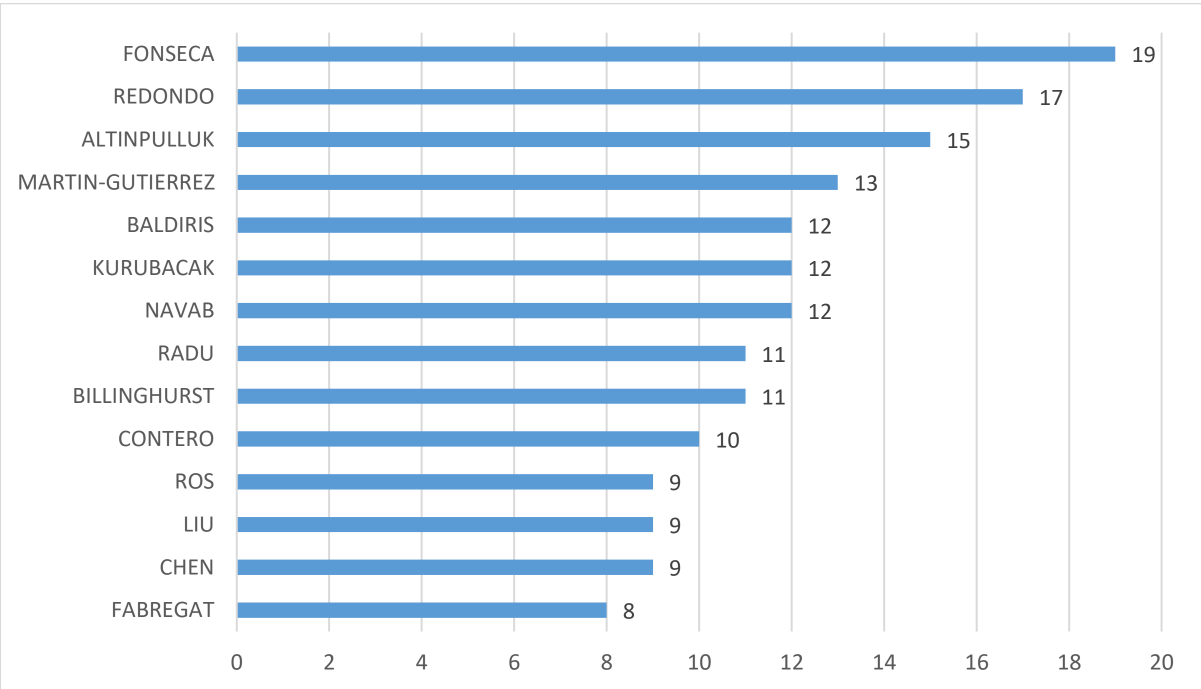

Figure 4. Number of studies of AR in education by author.

Figure 4 presents a list of the most influential authors of AR studies in education. We highlight that 6 out of the 15 authors are Spanish, including Dr. Baldiris, one of the advisers of this doctoral thesis.

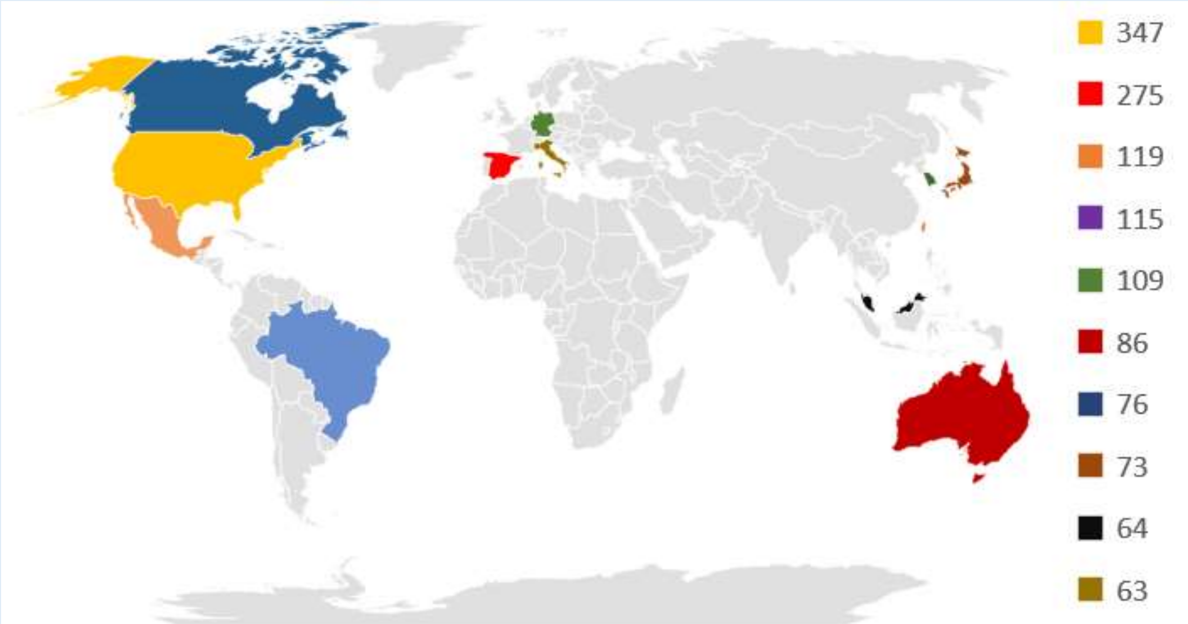

Figure 5. Number of studies of AR in education by country.

Similarly, Figure 5 presents a list of the most influential countries according to the nationality of the authors of the AR studies in education. We highlight that Spain is the second most influential country, only overpassed by the United States.

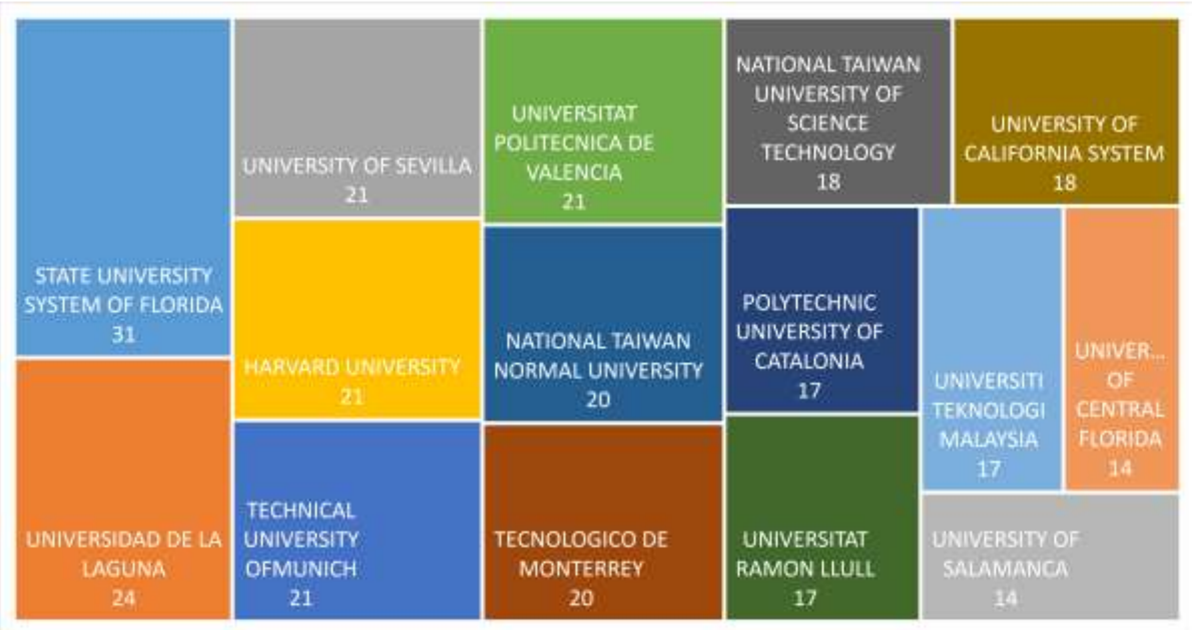

Figure 6. Number of studies of AR in education by university.

Finally, Figure 6 presents a list of the most influential universities according to the workplace where the research was carried out. We highlight that 6 out of 15 top universities are Spanish universities.

4.1.2 Levels of education

To identify the levels of education in which AR is most applied, we performed a systematic literature review of 61 studies published between 2012 and 2018 (see section 6). We classified each study according to the nine categories established by the International Standard Classification of Education (UNESCO, 2012) as shown in Table 3. Additionally, to identify the impact of AR in each level of education, we calculated the Cohen's *d* effect size (see section 8).

Table 3. Analysis of the status of AR according to the level of education.

Target group	Studies	Percentage (%)	Effect size (*d*)
Early childhood education	1	1.6	†
Primary education	19	31.1	.69 ($p < .001$)
Lower secondary education	11	18.0	.59 ($p < .001$)
Upper secondary education	9	14.8	.56 ($p < .001$)
Post-secondary non-tertiary education	0	0.0	†
Short-cycle tertiary education	1	1.6	.78 ($p < .001$)
Bachelor's or equivalent level	18	29.5	.83 ($p < .001$)
Master's or equivalent level	0	0.0	†
Doctoral or equivalent level	0	0.0	†
Not elsewhere classified	2	3.3	†

Table 3 indicates a similar distribution for children (*Early childhood education* and *Primary education*), teenagers (*Lower secondary education* and *Upper secondary education*), and *Bachelor's or equivalent level*. None of the selected studies consider *Post-secondary education non-tertiary education* or post-graduate education (*Master or equivalent level* or *Doctoral or equivalent level*) as target groups. Further, the study found that *Bachelor's or equivalent level* is the most benefited target group. There is only one study in the *Short-cycle tertiary education* category, and therefore, any conclusion would be biased. There was one study related to the *Early childhood education category*, but it did not provide enough data to calculate the effect size.

4.1.3 Fields of education

We identify the fields of education in which AR is most applied from the same systematic literature review shown in section 6. We classified the studies into 10 subcategories according to the broad fields of education proposed by the International Standard Classification of Education (UNESCO, 2012) as shown in Table 4. Additionally, to identify the impact of AR in each broad field of education, we calculated the Cohen's *d* effect size (see section 8).

† No available data

Table 4. Analysis of the status of AR according to the broad field of education.

Broad Field	Studies	Percentage (%)	Effect size (*d*)
Natural sciences, mathematics, and statistics	30	49.2	.62 (p < .001)
Arts and humanities	10	16.4	.82 (p < .001)
Social sciences, journalism, and information	7	11.5	.75 (p < .001)
Information and Communication Technologies	5	8.2	.39 (p < .001)
Engineering, manufacturing, and construction	4	6.6	1.24 (p < .001)
Health and welfare	4	6.6	.61 (p < .001)
Education	1	1.6	.27 (p < .001)
Business, administration, and law	0	0.0	‡
Agriculture, forestry, fisheries and veterinary	0	0.0	‡
Services	0	0.0	‡

Table 4 indicates that the most popular broad field of education is *Natural sciences, mathematics, and statistics*. Conversely, no study included the fields of *Business, administration, and law*, *Agriculture, forestry, fisheries and veterinary*, or *Services*. Further, the analysis found that *Arts and humanities* is the most benefited broad field of education. There is only one study related to the *Education* category, and therefore, any conclusion would be biased.

4.1.4 Advantages of AR in education

All the studies in the systematic literature review reported advantages when using AR in education as summarized in Table 5. However, it is important to clarify that these are only the most reported advantages and some studies reported more than one advantage.

Table 5. Advantages of AR in education.

Advantages	Number of studies	Percentage (%)
Learning gains	51	83.6
Motivation	46	75.4
Abstract concepts	16	26.2
Autonomy	16	26.2
Sensory engagement	14	23.0
Memory retention	9	14.8
Collaboration	8	13.1
Creativity	4	6.6
Accessibility	3	4.9

Available data, students and teachers alike indicate that learning gains is the most important advantage of AR in education. One of the possible reasons has to do with the second most reported advantage: *motivation*. Students affirm that using this novel technology is more motivating than using other pedagogical strategies, and consequently, their academic outcomes tend to improve.

‡ No available data

4.1.5 Disadvantages of AR in education

Fifteen percent of the studies analyzed in the systematic literature review reported some disadvantages when using AR in education (see Table 6). However, it is important to note that most of these disadvantages obey the fact that AR is a novel technology, and hopefully, as this technology continues to mature, most of these disadvantages will be overcome.

Table 6. Disadvantages of AR in education.

Disadvantages	Number of studies	Percentage (%)
Complexity	6	9.5
Technical difficulties	5	7.9
Multitasking	4	6.3
Resistance from teachers	2	3.2

The most reported disadvantage refers to the Complexity of using AR, especially when applied to children. Being a novel technology that involves multiple senses, becomes sometimes a very complex task especially for those who do not have technological abilities (Herpich et al. 2014). Additionally, some teachers participating in the studies claimed to have Technical difficulties when using AR in their classrooms which could cause resistance to use this technology in educational settings.

4.2 Impact of AR on education

To identify the impact of AR on education we conducted a meta-analysis of 64 empirical studies published between 2010 and 2018 (see section 8). We calculated the Cohen's *d* effect size based on the standard deviations, mean scores, and sample sizes provided by each study. Further, we performed a moderator analysis to evaluate the impact of AR compared to the pedagogical strategies of the control treatments and the impact of AR on special needs education (see section 9). The main results of the work performed to achieve this objective were published in the meta-analyses studies shown in section 8 and in section 9. In this subsection, we synthesize some of the most significant results.

One of the main challenges of our meta-analysis is that we integrate findings across studies with different research designs. First, the Pretest-Posttest-Control design in which participants are assigned to experimental or control groups, and each participant is evaluated before and after the treatment. Second, the Posttest Only with Control design in which participants are assigned to experimental or control groups but does not include a pretest. Third, the Single-Group Pretest-Posttest design that does not include a control group but evaluates participants before and after the treatment (Garzón & Acevedo, 2019). However, as established by Ray & Shadish (1998) effect sizes from different research designs cannot be directly compared as they estimate different population parameters. Therefore, we followed the guide proposed by Morris and DeShon (2002) for calculating *d* values from different research designs. Table 7 summarizes the effect size path coefficients for all the studies.

Table 7. Synthesis of the meta-analysis.

Variable	Overall
Number of samples	64
Total sample size	4705
Effect size	.68
Probability value	<.001

The guidelines for interpreting the effect size values are $d = .2$ (small effect), $d = .5$ (medium effect), $d = .8$ (large effect) (Cohen, 1992). The overall effect size of $d = .68$ indicates that AR has a medium impact on education. The combined effect of the 64 studies was calculated using the random-effects model. The motivation for this assumption was that the samples in individual studies were taken from populations that had varying effect sizes (Hedges, 1982). The found probability value ($p < .001$) indicates the rejection of the null hypothesis of homogeneity and led us to accept the alternate hypothesis of heterogeneity, which supports our assumption of the random-effects model.

4.2.1 Control treatment

To identify that the impact of AR on education is not the result of any intervention, but the result of the intervention with AR technologies, Santos et al. (2014) recommended that future studies should include the analysis of the control treatment as a moderator variable. Consequently, we compared the effects of the AR treatments against the treatments applied in the control groups.

We classified the control treatments in three categories: 1) *Multimedia* that refers to educational resources that uses different content forms such as videos, images, animation, and learning objects, 2) *Traditional Lectures* that refers to curriculum-based and lecture-based teaching, and 3) *Traditional Pedagogical Tools* that refers to traditional educational resources that teachers use to complement their lectures. Considering that Single-Group Pretest-Posttest research design does not include a control group, the comparison included only Posttest Only with Control and Pretest-Posttest-Control research designs. Table 8 summarizes the effect size path coefficients according to the control treatment.

Table 8. AR vs Control treatment.

Variable	Multimedia	Traditional Lectures	Traditional Pedagogical Tools
Number of samples	18	17	13
Total sample size	1751	1277	916
Effect size	.67	.61	.61
Probability value	<.001	<.001	<.001

Results from Table 8 show that using AR technologies is more effective than using other pedagogical strategies. Therefore, the improvement in student scores seems to be related to the use of AR and not only to the intervention.

4.2.2 Special needs education

To identify the impact of AR on special needs education we conducted a meta-analysis of 12 empirical studies published between 2010 and 2018 (see section 9). We calculated the Cohen's *d* effect size based on the standard deviations, mean scores, and sample sizes provided by each study. In this study, students with special needs refer to students who have some type of disability. Accordingly, we considered four types of disabilities, namely, vision impairment, deaf or hard of hearing, intellectual disabilities, and physical disabilities. Table 9 summarizes the effect size path coefficients.

Table 9. Impact of AR on special needs education.

Variable	Overall
Number of samples	12
Total sample size	270
Effect size	.75
Probability value	<.001

Results shown in Table 9 indicates that AR has a medium to large impact according to Cohens' classification. Due to the small sample, we did not perform an analysis of each type of disability. Consequently, we stress the importance that future research considers students with special needs as a target group.

4.3 Analysis of the pedagogical strategies

To identify the pedagogical strategies of AR interventions that best favor students' learning gains, we conducted a meta-analysis of 46 empirical studies published between 2010 and 2019 (see section 10). We calculated the Cohen's *d* effect size based on the standard deviations, mean scores, and sample sizes provided by each study. Further, we performed a moderator analysis to identify the effect of moderating variables such as learning environment and intervention duration. The main results of the work performed to achieve this objective were published in the meta-analysis shown in section 10. In this subsection, we synthesize some of the most significant results.

4.3.1 Pedagogical approach

Evidence from the literature shows that Constructivism is the most popular learning theory in educational technology (T. Anderson, 2016; Duffy & Jonassen, 2013). Constructivism is an approach to learning that states that people actively construct knowledge, and that reality is determined by the learner's experience. There is a significant number of approaches to learning that derive from the principles of constructivism; however, the most common pedagogical approaches in AR interventions are Collaborative learning, Inquiry-based learning, Situated learning, Project-based learning, and Cognitive theory of Multimedia learning (Saltan & Arslan, 2017; Wen & Looi, 2019).

We grouped the studies according to the pedagogical approach that accompanied each intervention. In case a specific intervention included elements of different approaches, we identified the main approach in that specific intervention (see section 10). It is important to mention that all the studies included in our meta-analysis fall into one of the five pedagogical approaches listed above. Table 10 synthesizes the results of the meta-analysis according to the pedagogical approach in each AR intervention.

Table 10. Effect of AR according to the pedagogical approach.

Pedagogical approach	Studies	Effect size	*p-value*
Collaborative learning	8	.85	<.001
Inquiry-based learning	8	.73	<.001
Situated learning	15	.59	<.001
Project-based learning	6	.74	<.001
Cognitive theory of Multimedia learning	9	.76	<.001

These results suggest that learning outcomes could be more reliable on the *Situated learning* approach, as this is the most popular learning approach. However, the results indicate that *Collaborative learning* is the most beneficial approach in AR interventions.

4.3.2 Learning environment

The analysis of this moderator variable is important to establish whether the effect of the pedagogical approaches differs depending on the context in which interventions are carried out: formal settings (classroom, laboratory), informal settings (field trips, museums, outdoor activities), or unrestricted settings (including both formal and informal settings) (Chauhan, 2016). This analysis provides insights on what characteristics of the environment surrounding the learner creates a more favorable learning setting. As shown in Table 11, we classified the studies according to the learning environment in each study.

Table 11. Effect of AR according to the learning environment.

Learning environment	Studies	Effect size (*d*)	*p-value*
Formal settings	32	.71	<.001
Informal settings	13	.73	<.001
Unrestricted settings	1	.79	<.001

These results suggest a small advantage of performing AR interventions in informal environments outside of classrooms or laboratories. There is only one study in the *Unrestricted settings* category, and therefore, any conclusion would be biased.

4.3.3 Intervention duration

This moderator variable was analyzed to determine whether the effect of the pedagogical approaches differs depending on the duration of the AR intervention. The analysis of the intervention duration is important to inform teachers and researchers on how long AR interventions should take, or what is the expected result given a specific duration. We considered the four categories of time recommended by Chauhan (2016), namely, One day; > One day < one week; ≥ One week < one month; and ≥ One month (see Table 12).

Table 12. Effect of AR according to the intervention duration.

Intervention duration	Studies	Effect size (*d*)	*p-value*
One day	23	.64	<.001
≥ One day < one week	1	.67	<.001
≥ One week < one month	9	.95	<.001
≥ One month	12	.69	<.001
Not specified	1	.61	<.001

These results indicate a greater impact on interventions that lasted between one week and one month. The results for the "≥ One day < one week" category are not reliable as the sample size is too low. Additionally, one study did not specify the duration of the intervention.

4.4 Design principles to develop AR educational applications

This subsection presents some principles to consider when designing AR applications to provide effective pedagogical tools that enrich educational environments. Additionally, we present some insights regarding the design of AR educational interventions to accurately implement AR applications. Finally, we describe the experience of development and subsequent validation of ARtour, an AR-based educational resource to promote eco-agritourism – namely, to promote agritourism while encouraging tourists to be environmentally responsible. This experience validates the design principles and intervention insights to provide evidence of the multiple affordances of AR technologies in education.

4.4.1 Design principles

These principles focus on specific strategies that instructional designers can consider when developing AR educational applications. Different studies have proposed design strategies to ensure that AR applications comply with technical and academic quality, hence we highlight two important studies that have guided the development of several applications. First, the study by Dunleavy (2014) proposed three specific design principles that designers should follow when developing AR applications. The study states that AR applications must 1) challenge students with high-level problems, 2) engage students with academic content driven by gamification, and 3) encourage curiosity, making visible the invisible. Second, the study by Endsley et al. (2017) proposed some aspects that designers must consider when developing AR applications so that they can be successfully integrated into educational environments. The study states that AR applications must 1) minimize overload, 2) adapt to user motion, 3) fit with user's physical abilities, 4) fit with user's perceptual abilities, and 5) account for hardware capabilities.

In this thesis, we propose four design principles related to instructional design, usability, accessibility, and software development. These principles seek to guide the development of AR applications that are effective in enriching teaching and learning processes. Next, we explain the importance of these principles and give instructions on how to implement them in the development of AR applications.

Instructional design.

The design of an AR application must go beyond its technical efficacy. Most AR applications are developed by professional programmers and consequently, their quality in terms of technology is out of discussion. However, what is important in this regard, is not only that these systems work properly but that they fulfill the purpose of education. Engineers have skills for technical issues such as designing, programming, assembling, among others, nonetheless, these skills are not enough to satisfy the pedagogical matters. On the other hand, pedagogical experts usually do not have the capacity to develop these tools, because they lack the programming and assembling skills. Therefore, to design AR applications that are technically efficient and pedagogically accurate, it is advisable to involve an interdisciplinary group of professionals, each one of whom is responsible for developing a specific activity under the guidelines of an IDM. These models propose a series of common rules to maximize the software creation process through five stages: analysis, design, development, implementation, and evaluation (Herrington & Oliver, 2000).

Instructional design is considered to fill the gap between effective pedagogical applications and average applications that are designed without explicit learning purposes (Khalil & Elkhider, 2016). It focuses on learner's experience and on how to make knowledge stimulating, memorable, and meaningful for life. Thus, IDMs translate the general principles of learning to provide a procedural framework for developing effective pedagogical material that yields successful learning outcomes.

One of the most relevant criticisms to IDMs has to do with the fact that most models are linear and static. Therefore, we recommend nonlinear IDMs that comprehends holistic approaches that decompose complex tasks into simpler and smaller elements. Another important feature of nonlinear IDMs is its iterative nature, which allows refining the design based on feedback and evaluation. Perhaps the three most successful IDMs to develop AR applications are the Four component instructional design (4C/ID) (van Merriënboer & Kester, 2014), the ARCS model (Keller, 1987), and the ADDIE model (Peterson, 2003). Consequently, designers should consider applying any of these models to generate technically efficient and pedagogically accurate AR applications.

Usability.

The most reported challenge of AR in education refers to the complexity of using AR systems, especially when applied to children or people with low technological abilities (Akçayir & Akçayir, 2017; Herpich et al., 2014; Radu, 2014). This technology involves multiple senses and requires simultaneous tasks from students, which may overload their attention affecting the usability of AR systems (Akçayir & Akçayir, 2017). Therefore, it is important to consider design strategies that favor the usability of AR applications to ensure that they can be easily implemented in any educational context. In this sense, one of the most visible benefits of including IDMs in the development of AR applications is that these models improve AR applications' usability (Kim, Billinghurst, Bruder, Duh, & Welch, 2018; Saltan & Arslan, 2017). Usability refers to the quality of a user's experience when interacting with the application. It is an aspect related to the ease of use of the application that seeks to ensure that the end user does not overstrain or encounter problems when utilizing the application (Bevan, Carter, & Harker, 2015).

A key factor in the development of highly usable applications is understanding the needs of the target users; therefore, it is advisable to employ user-center design from early in the design process (M. R. Endsley & Jones, 2016). One of the most complete studies regarding AR applications' usability was developed by Ko, Chang, and Ji (2013). The study proposed the following five groups of usability principles for smartphone AR applications and usability principles for the tangible user interface. First, User-information, which includes indications on the hierarchy to present the contents, the use of proper language, and multimodality to present the contents. Second, User-cognitive, which is related to cognitive aspects required to minimize memory and cognitive overloads. Third, User-support, which includes providing instructions for use, a help section, a friendly and adaptable interface, and support for potential errors. Fourth, User-interaction, which is related to the responsiveness of the application, the ability to provide feedback to users, and the need to minimize users' effort when using the application. Fifth, User-usage, which seeks to guarantee availability, context-based interface design, and fluency in navigation. These principles have successfully guided the development of multiple usable AR applications and, accordingly, we highly recommend it.

Accessibility.

It refers to the design of applications in a way that can be used by all the people regardless of their specific needs. In education, the term special needs refer to students who have some type of disability including vision impairment, deaf or hard of hearing, intellectual disabilities, and physical disabilities. According to the World Health Organization, over a billion people have some form of disability, among which there are more than 285 million people with visual impairments and more than 360 million people who have disabling hearing loss (WHO, 2018).

Mobile technologies play a central role at providing autonomy to students with any type of disabilities. A study by Georgia Tech's Wireless Engineering Rehabilitation Research Center stated that

92% of people with disabilities use a "wireless device such as a cell phone or tablet" (J. Morris, Jones, & Sweatman, 2016). In this sense, the addition of accessibility features in AR applications has been claimed by different studies in order to bring the numerous advantages of this technology to a greater number of users (Bacca et al., 2014; Diegmann et al., 2015).

The most reported advantages of AR in especial education are motivation to learn, facilitating interactions, improving short-term memory, and learning gains. Therefore, given the multiple benefits of the AR in special needs education, stakeholders should take the opportunity to promote the development of accessible AR applications that can be used by a greater number of users regardless of their special needs. Many guidelines address accessibility issues, however, we highlight the *WCAG 2.1* (WAI, 2018), the *Ergonomics of human-system interaction* (ISO, 2008), and the *Universal Design for Learning* (Rose, 2000), as the main guidelines that developers can use to create accessible AR applications to address the special needs of any type of students.

Software development.

One basic notion of the software development process is the consideration of a Software Development Life Cycle (SDLC) model. There are a variety of models, each of which has advantages and disadvantages according to each specific scenario. There is no single model suitable for all AR educational resources, as even multi-purpose methods cannot be widely used due to some particularities of specific applications (Ruparelia, 2010). The most popular approaches to SDLC processes are the waterfall model, the iterative model, the spiral model, and the agile model.

The waterfall model is a cascade model in which the development process moves step by step in a linear flow. This is perhaps the simplest SDLC model and it is suitable for small-scale projects. There is a nonlinear variant of this model called V-model, which has been described as suitable for the development of AR educational applications (Wulandari, Pratama, Hasanah, & Yuniarti, 2019). The iterative model is a repetitive model in which developers create new versions of the resource for every cycle. Every iteration includes the development of a separate component of the system and after that, this component is added to the previous one to form a single and functional resource. This model is suitable for large-scale project that involve many resources and many stakeholders (Ruparelia, 2010). The spiral model combines the waterfall and iterative models. This model is very useful when the initial requirements are not clearly defined, which although is not recommended for the development of educational resources, may sometimes occur specially in small-scale projects. This model is mainly used for designing user interfaces and focuses on the application's usability, making it in a good choice for developing AR educational resources (Zulkifli, Alnagrat, & Mat, 2016). Finally, the agile model is a nonlinear model that divides the project into short and transparent iterations that allow for the quick release of the first version of the product. One of the most popular agile methodologies for developing mobile applications is Scrum, which is highly recommended for projects with limited resources regarding time and money (Soogund & Joseph, 2019).

In addition to defining a specific SDLC, the development of an AR application involves a set of technical characteristics, programming skills, and software development tools that must be considered by designers and developers. There are hundreds of tutorials, videos, and online courses that developers can access to learn about the process of creating an AR application. Similarly, we present some important considerations that can be used as an initial guide, especially for inexperienced developers.

Perhaps the most important consideration for starting an AR project is related to the developer's programing skills. Lack of programming abilities can be a barrier that prevents some teachers and researchers from developing their own AR applications to enrich the learning environments. In this sense, there are two common deployment strategies that can be considered to bring the AR application to life: the use of Unity, the most popular engine to develop AR educational applications or the use of authoring tools, which eliminates the necessity for specific programing skills. Unity is recognized as the most popular and powerful game engine worldwide. This cross-platform game engine became popular for developing computer games; likewise, it has been used to design most AR educational applications (Linowes & Babilinski, 2017). This engine provides users the possibility to create games in both 2D and 3D and offers a primary scripting API in C# language.

Once all the features of the instruction have been defined, the designer must evaluate which software development kit (SDK) is required to create the AR application. There are many options, however, the main criteria for selecting a specific SDK are the type of license, supported platforms, Unity support, and tracking characteristics. Type of license refers to the costs associated with the license. Many SDKs offer free and commercial licenses, which differ in the functionalities of the application. People with low or null experience developing AR systems should consider the use of free open-source AR SDKs, which can be extended with new features proposed by developers. On the other hand, paid licenses offer multiple functionalities depending on the user's needs, allowing more complex and commercial applications to be developed. Supported platforms refer to the platforms that support the specific SDK. Almost any SDK supports Android and IOS platforms; however, some SDKs may encounter problems on Windows, macOS, and other platforms. Considering that most AR applications are developed in Unity, it is important to identify if a specific SDK is compatible with Unity. Finally, the tracking characteristics of an SDK indicate the type of objects that can be used to trigger the virtual information. The tracking characteristics may restrict the application to be marker-based or location-based.

There are many available SDKs such as ARkit, ARCore, Wikitude, DeepAR, EasyAR, and ARtoolkit; however, Vuforia is the most popular SDK for developing AR applications (Y. Chen et al., 2019). Vuforia is a SDK for mobile devices that uses Computer Vision Technology to recognize and track planar images and 3D objects in real time. This capability allows developers to position and orient virtual objects such as 3D bodies and other media to represent the academic content in relation to real world objects when they are focused by the camera of a mobile device. Vuforia supports 2D and 3D targets including markerless, images, 3D models, and a fiducial marker known as VuMark. The superior and stable computer vision techniques used by Vuforia allows it to efficiently detect and track multiple targets simultaneously, even in low-light conditions or in targets that partially covered. Vuforia provides Application Programming Interfaces (API) in C++, .Net, Objective-C++, and Java languages through an extension of the Unity game engine; therefore, it supports Android, IOS, and Windows platforms. Vuforia offers both free and paid licenses that differs in the functionality and the complexity of the applications that can be created from each of them.

Alternatively, authoring tools are important instruments that allow developers to create educational applications by using preprogrammed elements, eliminating the need for specific programming experience. Consequently, these tools are a reasonable option for novice users willing to engage in the development of an AR application. Some of the most common authoring tools are Aumentaty, Augment, and Aurasma, (Mota, Ruiz-rube, Dodero, & Arnedillo-Sánchez, 2018). However, it is important to consider that the resulting applications are somehow limited, regarding design, assessment modalities, augmenting modalities, traceability of students' performance, among others.

4.4.2 Insights into the design of AR interventions

Once the application has been designed, it must be implemented in a specific educational environment. The success of the use of AR applications in education has been widely demonstrated, however, it is important to recognize that such success depends not only on the technical characteristics of the applications but also on the pedagogical strategies to implement them. Next, we present some insights into how AR applications can be implemented in educational interventions, in order to obtain the best of this technology to enrich teaching and learning processes. These insights are based on our experience of validation of ARtour and as a result of the quantitative analysis of the studies in the literature reviews conducted during this thesis.

- The lack of formal instructional approaches when applying AR to learning activities tends to confuse and frustrate students, therefore, each AR intervention should be accompanied by a pedagogical approach to enrich the learning process.
- Evidence from literature indicates that the most appropriate learning theory for AR interventions is Constructivism in any of its representative instructional approaches (Situated learning, Collaborative learning, Inquiry-based learning, Project-based learning, and Cognitive theory of multimedia learning).
- As a rule, Collaborative learning is the instructional approach that most benefit AR interventions in each field of education; however, Situated learning is the approach that most benefits the field of Engineering.
- There is no pedagogical approach that benefits the most a particular level of education, that is, the target group should not influence the decision to choose a specific pedagogical approach.

- The use of AR in informal environments such as in field trips, outdoor activities, visits to museums, among others, have a larger impact on students' learning gains compared to formal activities inside classrooms or laboratories.
- The only field of education that benefits the most in formal environments compared to informal environments is the field of Social sciences.
- There is no learning environment that benefits the most a particular level of education, that is, the target group should not influence the decision to choose a specific learning environment.
- Duration is a very important variable in AR interventions, which influences students' learning gains. Although most interventions last two or fewer hours (one-shot interventions), the best results are obtained when interventions take between one week and one month.
- The implementation of longitudinal studies (interventions that last more than one month) does not yield better results than other categories of intervention duration. However, these studies are important to discard the novelty effect of AR and identify its real effect on education. The implementation of longitudinal studies is more advisable when the intervention involves Bachelor students, formal settings, and subjects related to Social sciences.

4.4.3 Validation of the design principles: "ARtour"

Both the design principles for the development of AR applications and the insights for the design of AR interventions were validated through the development of ARtour (see sections 11, 12, 13). ARtour is an AR-based educational resource that is expected to improve teaching and learning processes in an unexplored field of education: Agriculture. In the same line, the application is intended to accompany the learning process of vocational education students, one of the least explored levels of education.

The development of ARtour was grounded in the theory of situated learning (see section 13). Situated learning is a theory that poses that learning is situated within authentic activities and contexts (Lave & Wenger, 1991). According to this theory, learning takes place in the same context in which it is applied and, therefore, some authors describe it as a key complement to active learning methodologies (Agnderson, Reder, & Simon, 1996; Korthagen, 2010).

Educational content.

The main purpose of ARtour is to promote agritourism while encouraging tourists to be environmentally responsible. Agritourism has been defined as rural tourism conducted on working farms, in which tourists are encouraged to experience agricultural life firsthand (Phillip, Hunter, & Blackstock, 2010). It includes activities such as milking a cow, horse-riding, harvesting a crop, pick-your-own food, among others. In economic terms, agritourism includes different markets such as fishing agritourism, business agritourism, therapeutic agritourism, and sustainable agriculture.

The Food and Agricultural Organization of the United Nations (FAO) has been promoting agritourism in the form of sustainable agriculture. FAO asserts that changes in agricultural and food systems are required worldwide, to guarantee global food security at large (FAO, 2017). In this sense, as an alternative for producing vegetables, fruits, and protein, FAO promotes the implementation of *aquaponics*, a technique that has its place within the context of sustainable agriculture.

Consequently, the educational content of ARtour is focused on aquaponics. Aquaponics is an emerging agricultural technology that combines aquaculture (fish farming) with hydroponics (cultivation of plants without soil) in a symbiotic system. Nutrient-rich aquaculture water is recirculated through hydroponic growing beds. All the nutrients required by the plants are supplied through the fish wastes, eliminating the need for fertilizer. Likewise, the plants clean the water for the fish, eliminating the need for water exchanges. An aquaponic system is composed by a fish tank (aquaculture), a hydroponics system (hydroponics), a system of recirculation of water, and a filtration system. Figure 7 presents the “welcome” scene. In this scene, ARtour invites users to learn about the basic concepts of aquaponics.

Figure 7. Welcome scene.

Resource development.

The educational resource was developed following the guidelines of the ADDIE IDM, because unlike other models, ADDIE is a non-linear and flexible model where each stage interacts with each other (Allen, 2017) (see section 12). Next, we describe the work done at each stage and the validation process in the context of a case study.

A) Analysis

We defined vocational education students as the target audience because of their potential to develop sustainable agricultural strategies (Somerville, Cohen, Pantanella, Stankus, & Lovatelli, 2014). However, it can be reused in different educational contexts and has no limitations to be used by other types of users. We analyzed the characteristics of the target audience, their specific needs, and the prerequisites for using the application. To achieve an impact on most of the population, we decided to design the application for the Android platform, as it is the most widely used operating system worldwide, and it is affordable for a large part of the population.

B) Design

With the help of two experts in aquaponics, we defined the learning goals, the structure of the educational resource, the thematic contents, and the assessment instruments. According to the purpose of this thesis, the learning goal of the application is to serve as a pedagogical tool to teach aquaponics, in order to promote agritourism. The structure of the resource comprehends four levels that correspond to subtopics of aquaponics: 1) aquaculture, 2) hydroponics, 3) aquaponics system and, 4) eco-education. Each level matches a fixed station in the real aquaponic system: the fish tank (aquaculture), the hydroponic system (hydroponics), the recirculation system (aquaponics system), and the filtration system (eco-education). Each station contains four numbered trigger images (markers), each of which presents information related to a specific issue (definition, importance, varieties, and functioning, among others). The learning contents are displayed when the user focuses the camera of the mobile device on the target images located in different parts of each station. In addition, the application provides a section of games in which users can practice what they have learned and, finally, an evaluation section to validate the efficacy of the learning process.

The application presents two different experiences: field experience and home experience. The field experience takes place in a specific aquaponic system. Alternatively, we provide a home experience that allows users to continue the learning experience beyond the field experience. The home experience is held on a web application that contains the same information as the field experience. However, instead of a physical aquaponic system, the web application contains images of an aquaponics system with trigger images added to the images of the system.

C) Development

To structure and present the contents, we chose the Unity cross-platform game engine considering important aspects such as price, documentation, supported platforms, and learning curve. A study conducted by Peters et al. (2016) describes Unity as the most cost-effective, flexible, and sustainable engine for developing AR applications, which reinforces our decision. Figure 8 presents an augmented scene in the field experience. In this scene, ARtour explains the definition of the concept of hydroponics (level 2 of the educational resource).

Figure 8. Augmented scene at level 2 in the field experience.

To superimpose the virtual elements into the real environment we used Vuforia (see Figure 8). Vuforia is the most widely used platform to develop AR applications (Linowes & Babilinski, 2017), which somehow becomes a guarantee to develop our educational resource. The Vuforia SDK is used to detect target images located in specific places in the aquaponic system and deploy the educational contents in the form of dialogues, videos, and visual overlays.

All the landscapes shown in each scene were created using the free and open-source vector graphics editor Inkscape. This graphics editor provides a clear and user-friendly interface, which translates into a low learning curve (Oualline & Oualline, 2018). Also, Inkscape has a rich community, which offers supports to overcome any possible inconvenience. Inkscape is a powerful software to create 2D vector graphics that can be scalable to almost any screen size, which is ideal for developing educational content.

ARtour, the main character of the application, was modeled using Blender. Blender is a free 3D computer graphics software toolset that supports modeling, rigging, animation, simulation, rendering, and compositing and motion tracking. The main benefits of Blender are its relatively low learning curve, its rendering process, its production render engine Cycles (that is ray-trace based), and the fact that comparative tools are property, which makes Blender a suitable software for the creation of 3D educational content (Bhawar, Ayer, & Sahasrabudhe, 2013). In addition to modeling the main character of the application, we used Blender to model all the textures and animations of each scene. Figure 9 presents an augmented scene at level 1in the home experience. In this scene, ARtour explains the importance of fish consumption.

Figure 9. Augmented scene at level 1 in the home experience.

D) Implementation

The implementation of the application was held in the context of a case study whose purpose was to validate the effectiveness of the educational resource as a pedagogical tool (see section 13). The experience was carried out in a greenhouse aquaponics system located in an agritourism farm in northwestern Colombia. The study included 40 vocational education students ($M = 25.86,\ SD = 6.31$) who were randomly assigned to the experimental group or the control group. The students did not know which group they belonged to, nor did they know of the existence of another group. Both groups were guided by the same professor to eliminate the confounding factors on the experimental results of different personalities, teaching styles, and teaching methods. The professor is a doctor in biology whose research has focused on aquaponics during the past eight years.

The study compared the scores of students who received instructions using a combination of the resource and the professor's guidance (experimental group) to those of students who received instructions only from the professor (control group). This experiment sought to identify the impact of ARtour on the students' learning gains, the motivation of the students to learn about aquaponics, and the students' satisfaction to use the resource.

The measurement tools included pretests, posttests, follow-up test, motivation survey, and satisfaction survey. The pretest aimed to identify the students' previous knowledge of the topics included in the study. On the other hand, the posttest was designed to evaluate the learning achievement of the students after the treatment. Likewise, the follow-up test sought to identify the long-term impact of the treatment on students' learning. All three tests consisted of 20 multiple-choice questions with a set of 4 possible answers each. The tests included five questions on each topic (aquaculture, hydroponics, aquaponics system and, eco-education) and had a maximum score of 100. Additionally, we used the Instructional Materials Motivation Survey (IMMS) (Keller, 2009) to measure students' motivation. Finally, to evaluate the students' satisfaction with the educational resource, we used an adapted version of the satisfaction survey proposed in the study by Joo-Nagata, Martinez Abad, García-Bermejo Giner, and García-Peñalvo (2017).

Both the experimental and the control treatments included three stages: pre-field trip meeting, field trip, and post-field trip meeting. The pre-field trip meeting took place three days before the field trip. The students were gathered in a university classroom to receive information about the study, and then they took a pretest. The field trip was held in the context of a three-hour visit to an agritourism farm to learn about aquaponics. The system has an area of 56 m^2 and is composed of an aquaculture system, a hydroponic system, and the piping system. The aquaculture system comprises four tanks to raise tilapia: two with a capacity of 10000 m^3 each and two with a capacity of 2000 m^3 each. The hydroponic system comprises three beds of 1 m^2 each and a PVC piping system with a total length of 36 m. The hydroponic system produces tomatoes, lettuce, pepper, corn, onions, and carrots (see Figure 10). Additionally, the aquaponic system is complemented by a recirculation system and a filtration system.

Figure 10. Exploration of the aquaponics system.

The experimental treatment was carried out as follows. The students were gathered outside the greenhouse aquaponic system, where they were instructed on how to use the educational resource and received instructions about the process. Each student was provided with a smartphone, which contained the application. Then, they were instructed to move through the aquaponic system following the target images in ascending order as shown in Figure 10.

When a student scanned a trigger image, the system superimposed digital information. This information was presented in the form of dialogues, videos, and visual overlays (see Figure 11). At any time during the exploration, the students could ask questions regarding aquaponics. Besides, although the physical space was wide enough so that no scanning station was saturated, each student could stay for a maximum of 25 minutes. At the end of the activity, the students were instructed to explore the application in their homes using the home experience mode for the next two days (see Figure 12).

Figure 11. Augmented scene at level 1 in the field experience.

Figure 12. Augmented scene at level 2 in the home experience.

On the other hand, the students in the control group were gathered in the aquaponic system to receive instruction directly from the professor. At first, the students received basic information about the process and then they followed the teacher through the aquaponic system for each station: 1) the fish tank, where the professor explained about aquaculture; 2) the Hydroponic system, where the professor explained about hydroponics, 3) the recirculation system, where the professor explained about the aquaponic system; and 4) the filtration system, where the professor explained the ecological education module. The explanation in each station lasted around 25 minutes. At the end of each section, the students had the opportunity to ask questions about different aspects of the system. Finally, the students received a list of books and videos to study the contents in their homes during the following two days.

Finally, the post-field trip meeting was held three days later in the same location as the pre-field trip meeting. All the students took the posttest, completed the IMMS and the students in the experimental group fulfilled the satisfaction survey. One week later, the students took a follow-up test in the same location as the pre-field trip meeting. It is important to mention that all the activities with the control group were carried out at a different time than the experimental group.

E) Evaluation

To evaluate the impact of the educational resource as a pedagogical tool, we compared the scores of the students of the experimental and control groups. We used the means (*M*) and standard deviations (*SD*) in pretests and posttests (see Table 13) to measure the impact of the resource on the learning gains of the students (see Table 14).

Table 13. Summary of the results in the pretest and the posttest.

Group	*N*	Pretest		Posttest	
		M	*SD*	*M*	*SD*
Experimental	20	32.01	12.39	72.25	9.15
Control	20	34.50	8.93	69.75	6.42

Table 14. Impact of ARtour on students' learning gains.

Variable	Overall
Total sample size	40
Effect size	.63
Probability value	<.001

The calculated *d* value was found to be .63, which corresponds to a medium effect according to Cohen's classification. Additionally, we calculated the long-term impact of the course according to the learning methodology using the scores of the follow-up test (see Table 15). As shown in Table 16, a significant difference was found between the experimental and control groups, indicating that ARtour favors the long-term knowledge retention of students.

Table 15. Summary of results in the follow-up test.

Group	*N*	Follow-up test	
		M	*SD*
Experimental	20	69.00	9.43
Control	20	63.25	7.79

Table 16. Effect size analysis for the follow-up test.

Variable	Overall
Total sample size	40
Effect size	.95
Probability value	<.001

In the follow-up test, the grades of the experimental and control groups decreased with respect to the posttest. However, the average score of the experimental group remained higher than the average score of the control group and higher than the average scores in the pretest. The calculated effect size for the follow-up test was 0.95, which corresponds to a large effect size following Cohen's classification.

Likewise, we measured students' motivation using the IMMS. This instrument includes 36 questions in four subscales, namely attention, relevance, confidence, and satisfaction to compare the motivation of students when guided through different methodologies. Table 17 summarizes the results of effect size analysis for the four subscales of the IMMS.

Table 17. Effect size analysis according to the four subscales of the IMMS.

Subscale	Group	*N*	*M*	*SD*	*d*
Attention	Experimental	20	3.78	.61	1.19 ($p < .001$)
	Control	20	3.12	.49	
Relevance	Experimental	20	3.86	.53	1.21 ($p < .001$)
	Control	20	3.23	.51	
Confidence	Experimental	20	4.02	.48	1.70 ($p < .001$)
	Control	20	3.16	.53	
Satisfaction	Experimental	20	3.55	.54	.67 ($p < .001$)
	Control	20	3.21	.48	

The results indicate that ARtour has an average large effect size on the students' motivation to learn about aquaponics ($d = 1.19$). As for the motivation factors, Attention ($d = 1.19$), Relevance ($d = 1.21$), and Confidence ($d = 1.70$) showed a large impact and the Satisfaction factor ($d = .67$) showed a medium impact on students' motivation.

After completing the IMMS, the students of the experimental group were asked to evaluate the learning experience through the satisfaction survey. It consists of 10 statements that use a 7-point Likert scale. Each level ranges from strongly disagree (1) to strongly agree (7). This survey was validated and used in other investigations (Joo-Nagata et al., 2017) and modified to be applied in this study as shown in Table 18. Figure 13 summarizes the results of the scores given by the students.

Table 18. Satisfaction survey.

Item	Description
Item_1	I was comfortable using the resource
Item_2	It was easy to focus the target images
Item_3	The information displayed in the resource is accurate
Item_4	The resource has given me a positive impression about aquaponics
Item_5	The resource has given me important information for my learning
Item_6	It is easy to use the application
Item_7	I was given enough information for the use of the resource
Item_8	I like the information that shows the resource
Item_9	The graphic design of the resource is visually appealing
Item_10	I liked this field trip better than studying in the classroom

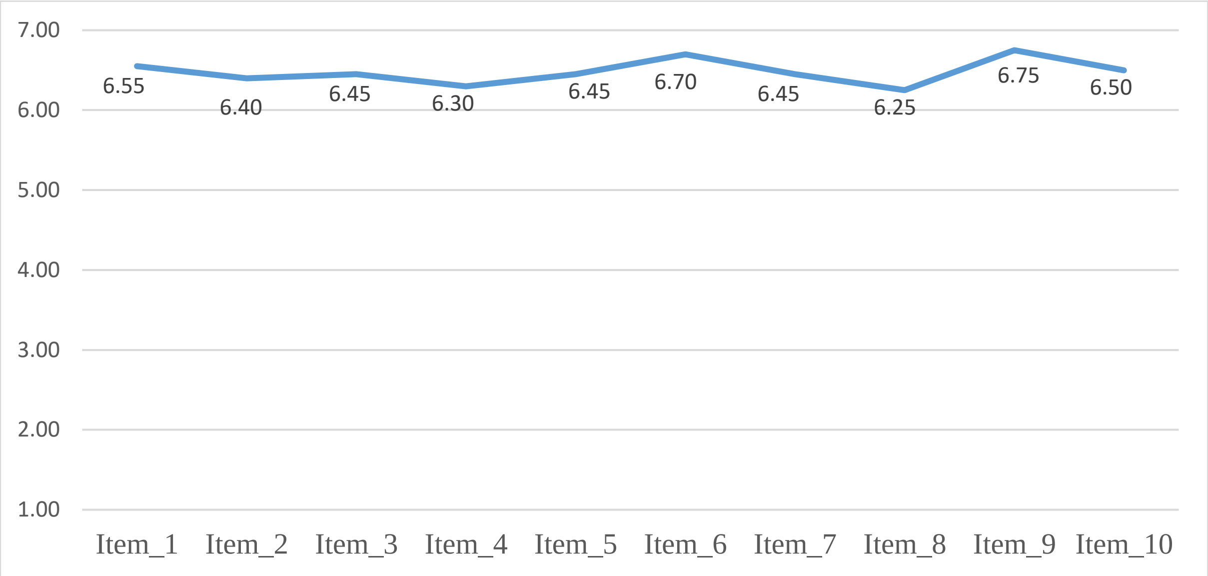

Figure 13. 7-point Likert scale satisfaction survey.

The results of the satisfaction survey show an average of 6.48 (out of 7), which indicates that the users felt satisfied with the resource. We can notice that the Item_6 and the Item_9 are the items with the greatest acceptance. These items have to do with the ease of use of the application and its visually appealing graphic design. We highlight that no item had a score lower than 6, which indicates a strong user satisfaction when using the resource.

5. Discussion

This thesis contributes to the understanding of AR technology as an important tool to develop effective educational resources to enrich educational settings. The findings throughout the research work carried out for three years, happen to be relevant to different aspects of educational technology. The thesis makes significant contributions to theory and practice, which have been endorsed by different major scientific journals. This section discusses the results of the research process according to our research objectives.

We analyze the results regarding the tendencies of AR applications in education. Subsequently, we discuss the impact of AR on education and the effect of the moderating variables on students' learning gains. Then, we highlight what pedagogical strategies best favor AR interventions. Finally, we describe some design principles to develop AR educational resources as pedagogical tools to improve teaching and learning processes.

5.1 Status and tendencies of AR in education

5.1.1 Trends in the number of AR applications for education

The number of studies of AR in education has increased significantly since 2010. This increase can be attributed to the integration of AR into mobile devices such as smartphones and tablets, which overcame one of the main challenges of initial AR applications for education: high costs. Ever since, AR applications have been successfully implemented in different fields of education and at different levels of education.

The number of studies that report the uses of AR in educational settings has increased along with the increase of AR applications (Akçayir & Akçayir 2017; Bacco et al. 2014; Chen et al. 2017; Diegmann et al. 2015), establishing a complete description of the uses, advantages, challenges, and opportunities of these systems for education. There is an average increase of 33 % of publications per year in the last ten years. Additionally, we highlight that the most significant increases happened in 2013 (61% with respect to 2012), 2015 (68% with respect to 2014), and 2017 (54% with respect to 2016). These positive figures seem to indicate that AR is an important technology that may be reaching maturity in education.

5.1.2 Analysis of target groups

Target groups refers to the level of education of the participants in each intervention. The analysis of this variable has been of great interest to the research community because it provides ideas on what type of users these applications should focus on. The results indicate that AR applications include, as target groups, Primary education students, Secondary education students, and Bachelor students in similar numbers. Our results seem to indicate that no specific ability is required to handle AR technologies, which is supported by the studies by FitzGerald et al. (2013) and Akçayir and Akçayir (2017), who pointed that one of the main advantages of AR applications is the ease of use of this technology. However, the results suggest a greater impact of AR on more mature students such as Bachelor students (d[§] = *.83*), compared with younger students of primary (d = *.69*) or secondary education (d = *.58*). Issues such as the complexity of using the systems, multitasking, and information overload can affect young users of AR applications (Akçayir & Akçayir, 2017; Garzón, Pavón, et al., 2019; Santos et al., 2014). On the other hand, our results indicate that, as stated in the study by Bacca et al. (2014), the number of AR applications that consider vocational education students is too low. The expansion of the global economy has caused that labor market requires specific skills from workers, increasing the demand for vocational professionals. It has been demonstrated that AR increases the depth of the instructions on even the more complex tasks, and therefore, training processes in industry can be reinforced using AR systems.

5.1.3 Analysis of fields of education

Field of education refers to the domain subject of the AR application in each study. The results indicate that the most common field of AR applications is *Natural sciences, mathematics and statistics.* Over 50% of the AR applications for education are designed to teach a topic related to this broad field of education (Bacca et al., 2014; P. Chen et al., 2017; Garzón & Acevedo, 2019). However, the highest impact was obtained in the broad field of *Engineering* (d = *1.24*). These subjects include abstract concepts that are more easily understood with the help of the special characteristics of AR, and consequently, developers and practitioners should focus their efforts on developing applications to facilitate the understanding of such contents (Garzón & Acevedo, 2019). On the other hand, we could not find evidence of the use of AR applications to teach subjects related to three broad fields of education: *Agriculture, forestry, fisheries and veterinary*; *Business, administration and law*; and *Services.* This finding represents a challenge to stakeholders in the search for innovative applications to expand the limits of AR in education.

5.1.4 Advantages of using AR in educational settings

The advantages of AR in educational settings go from psychological to learning aspects. All the studies analyzed in this thesis reported some kind of advantage when using AR in education. The most common advantage is that students improve their academic performance when using AR systems. This improvement has been reported not only by data but also for different teachers and the students themselves and has been identified by multiple review studies as the main advantage of AR in education (Akçayir & Akçayir, 2017; Bacca et al., 2014; P. Chen et al., 2017; Garzón, Pavón, et al., 2019). The

[§] d stands for effect size following Cohen's classification second most common advantage of AR in education is motivation. Results indicate that students feel more motivated to learn by using AR applications and are more willing to repeat the AR learning experiences compared to other pedagogical tools. This motivation may be a direct consequence of another very important advantage reported in multiple studies: *Sensory Engagement*. This is related to how children learn in their natural mode, using several of their senses in a constructive process. Another common advantage of AR in education has to do with the possibility of facilitating the comprehension of *Abstract Concepts*. This advantage has been reported by most studies related to the field of engineering, which argue that AR is ideal to explain things that cannot be observed. *Memory retention* has been also reported as an advantage of using AR in educational settings. This technology not only helps retain knowledge but also gives the student the possibility of retaining it for longer periods compared to other pedagogical strategies (Chiang et al. 2014; Sommerauer & Müller 2014; Zhang et al. 2014).

The aforementioned are only the most reported advantages in the studies that have been analyzed in this thesis, however, there is a larger list of advantages such as Autonomy, Collaboration, Creativity, and others, that have been identified by different studies. These advantages show the importance of using AR technologies in the teaching and learning processes and indicate the multiple benefits that this technology brings to education.

5.1.5 Disadvantages of using AR in educational settings

Notwithstanding the multiple benefits of the use of AR applications in education, there are still some challenges to be solved. The most reported disadvantage refers to the complexity of using AR, especially when applied to children. Being a novel technology, which involves multiple senses, becomes sometimes a very complex tool especially for those who do not have technological abilities (Herpich et al. 2014). This challenge has been pointed out in the studies by Radu (2012) and Akçayir and Akçayir (2017), who indicate that such complexity affects the usability of AR systems. However, the usability of AR systems and consequently the complexity of some applications could be improved by using IDM. Similarly, teachers participating in some studies manifested having technical difficulties when using AR in their classrooms. This may be caused by scarce technical training from part of some teachers to manage the AR systems, which could limit their use in educational environments. Another reported issue related to AR systems is Multitasking. As Radu (2012) indicated, students expressed that AR applications demand too much attention, which can be a distraction factor that causes students to ignore instructions or important stages of the experience. Finally, Resistance from teachers has been reported as a possible difficulty of the implementation of AR in educational environments, since some teachers may prefer having total control over the content, despite recognizing the benefits of using AR applications.

5.2 Impact of AR on education

One of the main findings of this doctoral thesis is that AR has a medium impact on students' learning outcomes according to Cohen's classification (see section 8). The analysis of 64 quantitative studies indicates that AR applications for education have an overall effect size of $d = .68$, which implies that AR has a positive impact on education. This result is aligned with the results of previous meta-analyses, which, with the exception of the study by Yilmaz and Batdi (2016), have stated that AR has a medium impact on education.

5.2.1 Control treatment

Results from Table 8 show that using AR technologies is more effective than using other pedagogical strategies, including other multimedia resources, traditional lectures, and traditional pedagogical resources. The effect was found to be $d = .67$ when comparing AR applications with multimedia resources; $d = .62$ when comparing AR applications with traditional lectures; and $d = .61$ when comparing AR applications with traditional pedagogical resources.

Additionally, we compared the results of our meta-analysis with similar meta-analyses that measured the effectiveness of other technologies on education (Garzón & Acevedo, 2019). Several meta-analyses have evaluated the impact of technology on students' learning effectiveness; however, we highlight the three most cited studies in the past 20 years. First, the meta-analysis by Christmann and Badgett (2003) who analyzed 68 empirical studies to measure the impact of Computer-Assisted Instruction (CAI) on the students' academic achievement. The study concluded that CAI has a low to medium impact on student's achievement ($d = .34$) compared to traditional instruction. Second, the meta-analysis by Liao (2007) who analyzed 52 empirical studies to measure the effects of CAI on students' achievement. The study concluded that CAI has a medium impact on student's achievement ($d = .55$) compared to traditional instruction. Third, the meta-analysis conducted by Chauhan (2016) who analyzed 122 empirical studies to measure the impact of technology on students' learning effectiveness. The study also concluded that technology has a medium impact on student's learning effectiveness ($d = .54$) compared to traditional instruction.

By comparing our results and the results of similar meta-analyses on the effectiveness of AR on education with the results in the meta-analyses on the effectiveness of other technologies on education, we conclude that AR has a higher impact on students' learning achievements according to Cohen's classification. This comparison suggests that although different types of technology have a positive impact on education, AR seems to have a greater impact on the learning gains of students.

5.2.2 Special needs education

We analyzed the impact of AR applications in special needs education (see section 9). This has been reported as one of the most important challenges of AR in education considering the limited number of

AR applications that consider the special needs of students (Akçayir & Akçayir, 2017; Bacca et al., 2014; Garzón, Pavón, & Baldiris, 2017). This analysis aimed at identifying the impact of AR on the learning gains of students with special needs, that is, we intended to show what are the benefits of using AR in special education or under what conditions AR should be used to complement it. The overall effect size of AR on the learning gains of students with special needs was found to be $d = .75$. The effect size was found to be large for all the subcategories according to Cohen's classification (Cohen, 1992). However, despite the apparent multiple benefits, the use of AR in special needs education is still too limited. Therefore, stakeholders have great opportunities to develop new and better systems that include all type learners.

5.3 Effect of the pedagogical strategies on AR interventions

The mean $d = .68$ of AR on students' learning gains found in this study must be interpreted carefully (Garzón & Acevedo, 2019). Although the overall result is promising, we must consider that the results in individual studies may vary depending on a wide range of reasons. Factors of AR interventions such as the pedagogical approach, the learning environment, the intervention duration, and others that were not considered in this study, may influence the results of each intervention. Next, we describe the effect of these factors on students' learning gains.

5.3.1 Pedagogical approach

The analysis of the pedagogical approaches that accompany AR interventions has been recommended by different studies (Turan, Meral, & Sahin, 2018; Wen & Looi, 2019). Although some qualitative reviews have analyzed which pedagogical approaches have been considered in AR interventions (Saltan & Arslan, 2017; Wen & Looi, 2019), the literature lacked quantitative analysis to measure the effect of each pedagogical approach on AR interventions. This study closed this research gap by analyzing, in the light of the learning theories, how pedagogical approaches affect the impact of AR on education.

Theoretical traditions have set four major learning theories, namely, Behaviorism, Cognitivism, Humanism, and Constructivism (Schunk, 2012). However, evidence from the literature shows that Constructivism is the most popular learning theory in educational technology and likewise, in AR interventions (T. Anderson, 2016; Duffy & Jonassen, 2013; Saltan & Arslan, 2017). Although there is a significant number of approaches to learning that derive from Constructivism, the most common pedagogical approaches in AR interventions are Situated learning (SL), Collaborative learning (CL), Inquiry-based learning (IBL), Project-based learning (PBL), and Cognitive theory of Multimedia learning (CTML) (Saltan & Arslan, 2017).

The results indicate that CL is the pedagogical approach that most benefits AR interventions ($d = .85$). Following Cohen's classification, this result means that CL has a large effect on students' learning outcomes. The effect size of the pedagogical approaches CTML and IBL was found to be medium to large ($d = .77$ and $d = .74$) indicating the positive impact of these pedagogical approaches in AR interventions. The effect was found to be medium for PBL ($d = .61$) and finally, the pedagogical approach that least favored AR interventions was SL ($d = .57$).

We performed a cross-analysis to identify the effect of the pedagogical approach depending on the field of education and the level of education. We used the broad fields of education and the levels of education proposed by the International Standard Classification of Education ISCED (UNESCO, 2012). The results indicate that the learning approach does not influence the students' learning outcomes in the fields of Arts and Humanities, Social Sciences, Natural Sciences, and Health. On the other hand, the field of Engineering, was more benefited from interventions that used the Situated learning approach. Similarly, the results do not show significant differences in students' learning outcomes according to the levels of education, that is, there is no specific learning approach that favors a specific level of education.

5.3.2 Learning environment

The analysis of the learning environment shows that the effect size of AR on education varies depending on the place where AR interventions are conducted. Current learning processes do not need to be restricted to a formal environment within classrooms or laboratories. Pedagogical tools, such as those provided by AR technologies, allow to successfully expand the limits of the educational institutions (Chauhan, 2016). Sometimes informal learning environments outside formal institutions offer special learning opportunities that are difficult to obtain inside specific formal environments. Such is the case for subjects like environmental education (Ballantyne & Packer, 2002; Manzanal, Rodriguez, & Casal, 1999), astronomy (Liou, Yang, Chen, & Tarng, 2017; Tarng, Ou, Lu, Shih, & Liou, 2018), and arts (K. E. Chang et al., 2014; Sommerauer & Müller, 2014), which have been declared to be more effectively learned when studied in informal environments. Consequently, the results of our meta-analysis indicate that the effect size was large in informal settings ($d = .82,\ p < .01$) and medium in formal settings ($d = .68,\ p < .01$). Only one study was conducted in a combination of formal and informal settings, and therefore, there is not enough information to determine the effect of this strategy.

5.3.3 Intervention duration

Some studies indicate that the impact of technological tools is more positive in brief duration interventions as highly artificial conditions can be created by researchers for a short period (Cheung & Slavin, 2013). In contrast, other studies indicated increased student performance scores over long periods of time because the continuous exposition to the pedagogical tools benefits the learning process (Chauhan, 2016; Wilson et al., 2019). Our results seem to contrast the previous findings because the highest effect size was obtained when the interventions lasted between a week and a month ($d = .98$). One day interventions and one month or longer interventions showed the same effect size of $d = .61$.

Only one study had a duration between a day and a week, and therefore, there is not enough information to determine the effect of this category. Similarly, one study did not provide information on the duration of the intervention.

5.4 Design principles

This thesis applies the findings of previous research to propose a set of design principles to guide the development of AR educational applications. The effective design of AR applications plays an important role in the learning process. There are specific design features that should be considered depending on the target students or the field of education being addressed. That is, AR applications are not magical bullets in educational environments; conversely, every application is unique and must be designed to be applied in a specific scenario

In addition to the design principles, we propose a set of insights to consider in the design of AR interventions. As stated in section one of this thesis, we pose that regardless of one's pedagogical preferences or philosophical perspective, it is essential to consider methods along with technology in research and in practice. That is, it is not enough to have a proper AR application, but it is necessary to use that application in a suitable context. Therefore, we propose a set of insights to guide the design of AR interventions to obtain the best of this technology for teaching and learning.

The development of ARtour and its subsequent implementation in the context of a case study served to validate both the design principles for the development of AR applications and the insights for the design of AR interventions. This educational resource fills two research gaps of AR in education. First, it focuses on aquaponics, a subject that belongs to the broad field of Agriculture, one of the least explored fields of education. Second, the application is intended to complement the education of vocational education students, one of the least explored levels of education in AR interventions. The development of the resource responds to the concept of the theory of situated learning. A theory that has proven to be suitable for teaching subjects related to environmental education (Agnderson, Reder, & Simon, 1996; Korthagen, 2010).

The case study included experimental and control groups, each of which took a pretest and a posttest. The results of the pretest revealed a similar academic level in each group. In the posttest, the students of both groups increased their scores with respect to the pretest which indicates that the students obtained significant learning gains on aquaponics, regardless of the learning methodology. However, the students in the experimental group obtained higher scores than students in the control group. The calculated effect size (d = .63) indicates that ARtour has a medium impact on education, which is in line with the results shown in Table 7. It also indicates that active learning methodologies conducted in outdoor learning scenarios positively affected students' outcomes, which confirms the findings in the studies by Michael (2006), Su and Cheng (2015), and Zhou and Purushothaman (2018).

The motivation survey showed significant differences in the four motivational factors in favor of the students in the experimental group. The attention factor reflects the students' interest in carrying out the activity, although they did not receive a specific reward for doing so. The confidence factor measures the students' feeling of control and their expectation for success in the activity. The satisfaction factor indicates the students' feeling about the AR-based educational resource. Finally, the relevance factor indicates what students think about the importance of the resource and how well the activity met their needs and goals. These findings are consistent with the findings of previous studies (Akçayir & Akçayir, 2017; Bacca et al., 2014; Garzón et al., 2019) that have shown that motivation is one of the more important advantages of using AR in educational settings.

We pose that using AR technologies in outdoor learning environments will allow teachers to use pedagogical approaches that might otherwise be difficult on field trips. This technology promotes autonomy, as students navigate through the trigger images on their own to explore and learn at their own pace. This technology provides enjoyment, because the learning content is presented in an interactive and multimedia format, and therefore the learning process becomes more pleasant. Finally, this technology promotes greater interaction with the object of study, which in our study is reflected in a positive attachment to nature.

Our findings indicate that an appropriate combination of active learning methods with AR-based educational resources benefits environmental education programs, whether in learning, motivation, or satisfaction. Therefore, given the numerous advantages of the use of AR technologies for education that have been shown in this and similar studies, we hope to encourage practitioners and policymakers to promote the use of this type of pedagogical tools to enrich environmental education programs.

6. Conclusions

The purpose of this doctoral thesis was to contribute to the understanding of AR technology as a tool to enrich educational settings. To achieve this purpose, we first identified the state of the art of AR in education, then we measured the impact of AR in education and the effect of moderating variables, and finally, we proposed some design principles to develop AR applications. Next, we present the main conclusions derived from the four research objectives of this thesis.

The analysis of 183 empirical studies published between 2010 and 2019, allowed us to identify the trends, uses, advantages, disadvantages, and challenges of AR applications in education. The number of published studies related to applications of AR in education has been steadily increasing since 2010. Since then, AR applications have been successfully implemented in different fields of education and with different target groups. The results indicate that the most common field of education is *Natural sciences* and, conversely, we could not find evidence of the use of AR applications to teach subjects related to the fields of *Business, administration and law* and *Services*. Likewise, the most common levels of education are *Primary education*, *Secondary education*, and *Bachelor education* and, on the contrary, we could not find evidence of the use of AR in *Post-secondary non-tertiary education*. Regarding the advantages, all the studies reported some benefit when using AR applications in education; however, the most reported advantages are learning gains and motivation. Finally, despite the numerous benefits of AR in education, there are still some challenges to be solved. The most reported challenge has to do with the fact that AR applications may be a complex task, especially for users with low technological skills. This complexity may affect the system's usability; therefore, it is important to implement strategies such as the use of an IDM to ensure proper usability of AR applications.

The quantitative analysis of the data indicates that AR has an overall medium impact on students' learning outcomes. However, there are moderating variables that cause this value to change from one study to the other. Variables such as subject, target group, learning environment, intervention duration, and special needs of the users can influence the results in each intervention. Our results indicate that AR is more effective when used to teach topics related to engineering. Similarly, the most benefitted target group happens to be bachelor students. According to the characteristics of the intervention, informal educational environments outside of classrooms or laboratories seem to favor the results in AR interventions more than formal environments. As for the duration, interventions that took between a week and a month showed the highest results, although the most common intervention duration was one day. The analysis also confirmed that AR has a large impact on learning gains of students with special needs. Additionally, this technology enriches special education environments with other important advantages such as motivation to learn, enjoyment, and autonomy.

Evidence from the literature shows that Constructivism is the most popular learning theory in AR environments. Particularly, the most common pedagogical approaches that derive from Constructivism are Situated learning, Collaborative learning, Inquiry-based learning, Project-based learning, and Cognitive theory of multimedia learning. The results indicate that despite Situated learning is the most widespread pedagogical approach, interventions that included the Collaborative learning approach obtained the higher scores. However, it is necessary to keep in mind that the results may vary from one study to the other depending on several factors. In this sense, interventions in subjects related to the field of engineering obtained the highest scores when Situated learning theory was included. Apart from this specific result, no particular learning approach influenced the students' learning outcomes in any particular field of education. Similarly, the results indicate that no particular learning approach influenced the students' learning outcomes in any particular level of education.

The analysis of the existing literature and our experience in the process of development and subsequent implementation of ARtour allowed us to identify some design principles to apply in the development of AR applications. These principles are expected to guide future development of AR applications that comply with technical and academic quality. In this sense, we proposed four design principles related to 1) instructional design, 2) usability, 3) accessibility, and 4) software development. First, we highlight the importance of using an IDM in the development process. These models translate the general principles of learning to provide a procedural framework for developing effective pedagogical material that yields successful learning outcomes. Second, to avert the complexity of using a specific AR application, it is important to ensure its usability. A usable application is not intended to be simple or easy to use, that is, usability is not about making things easy, it is about providing efficiency, effectiveness, and satisfaction. In this regard, to guarantee proper usability of the application, it is strongly recommended to guide the development process through the guidelines of an IDM. Third, given the numerous advantages of AR for education, it is important to extend its benefits to a greater number of users. For this purpose, we emphasize the need to create accessible AR applications that consider the special needs of users. In this thesis, we recommend the *Web Content Accessibility Guidelines,* the *Ergonomics of human-system interaction* and the *Universal Design for Learning* as the main guidelines to create accessible AR applications to address the special needs of any type of students. Fourth, we highlight two possibilities for the development of the software related to AR applications: the use of the combination Unity/Vuforia or the use of authoring tools. From our experience, Unity/Vuforia is the most efficient combination for developing AR applications. However, these development tools require relatively high programming expertise from developers. Alternatively, authoring tools allow developers to create AR applications by using preprogrammed elements, which eliminates the need for specific programming experience. Some of the most common authoring tools are Aumentaty, Augment, and Aurasma. However, developers must recognize that these tools limit the possibilities of the applications, as for design, assessment modalities, augmenting modalities, traceability of students' performance, among others.

Another important issue to consider when developing AR applications is development time. This is a key factor and depends mainly on the type and amount of educational content of the AR application. For instance, developing an Augmented Book (a typical AR educational application) takes more time than developing a basic application learn the vowels. Other important features that may be added to the AR application to improve the user's experience which may infer in the development time. Features such as native device (e.g. access to the gallery), user engagement (e.g. social sharing), log-in (e.g. email verification, password restoration), accessibility, multi-language support, and chat and forums, would imply a greater complexity and, consequently, would add extra time to the process. The decision to include any of the abovementioned features will determine the type of SDLC model to be used, the required programming ability from the developer, the implementation time and the final cost of the application. Our experience developing ARtour took around 12 months for all stages of instructional design. The analysis and design stages took around fifteen 15 days each. The development stage took approximately 8 months, due to our application includes all the features mentioned before. Also, the resource includes programing in Unity, Vuforia, Inkscape, and Blender, each of which implied a significant learning curve. Additionally, it is important to consider that the amount of educational content is relatively high, as the resource includes all the topics related to aquaponics. Finally, the implementation and evaluation stages were implemented simultaneously in the context of a case study and took around 30 days.

6.1 Implications for stakeholders

As AR technology gains importance in teaching and learning practice, the role of AR applications is becoming a primary focus of research initiatives. We argue that the findings of this thesis could be used to inform these initiatives, as it provides evidence from previous research and from our experience in the development and implementation of AR educational applications. We pose that in order to promote and integrate AR technology as an appropriate and effective way to support learning, the capacity and culture of using AR applications as a learning strategy must be built among stakeholders. Consequently, based on the findings in this thesis, we provide indications for students, teachers, researchers, and policymakers to enrich their experiences of using AR technologies.

Whether primary, secondary, or bachelor students, AR technology has been proven to be an efficient alternative to help learners improve their learning process. It helps not only to improve student's learning outcomes but also brings other important benefits such as autonomy, creativity, satisfaction, and more importantly, motivation to learn. The unique characteristics of AR help students understand abstract concepts that are much more difficult to understand with the help of other technologies or pedagogical tools. It provides easy access to phenomena such as the movement of the planets or the behavior of magnetic fields, which have been identified as troublesome for students. On the other hand, available data shows that the success of AR for improving students' learning outcomes depends on the attitudes of the students towards this technology. Hence, we encourage students to shift paradigms and give this technology an opportunity to assist them in their processes of knowledge acquisition.

This thesis provides different alternatives for the use of AR applications in student learning, which is a potential input for improving teaching practice. Given the apparent good results, it seems a good practice to foster collaborative activities when involving students in AR interventions. Similarly, the effectiveness of informal learning settings suggests that AR interventions should be conducted more frequently as part of informal activities, rather than limiting the use of AR to classrooms and laboratories. The results also indicate that AR interventions that lasted between one week and four weeks produced better results in students' outcomes. However, a specific intervention duration may not work for each intervention. Additionally, the results show that Informal settings was more effective when the intervention lasted one or more months, and in contrast, Formal settings was more effective when the intervention lasted one day. Moreover, the effect of AR on students' learning outcomes does not depend on the level of education or the field of education in AR interventions. However, the field of Social sciences seems to benefit most from the Formal settings learning environment and the field of Engineering seems to benefit most from the Situated learning pedagogical approach. To conclude, teachers are encouraged to identify, according to their needs and possibilities, an appropriate combination of the intervention characteristics to obtain the best of AR to enhance their classes.

The analysis of the existing literature reveals the state of the art of AR in education, which constitutes an important contribution to researchers who are seeking suitable topics to explore. Perhaps, the most relevant indication to researchers is the importance of implementing an IDM in the development process of AR applications. This will allow an adequate translation of learning principles into effective pedagogical applications and will ensure vital features such as usability and accessibility. Regarding accessibility, we highlight the need for including features that allow any user to use AR applications, regardless of their limitations and considering their preferences and needs. Including accessibility features will expand the affordances of AR to a broader public and will be a step forward in terms of social inclusion. Additionally, the results show no evidence of the use of AR applications that include short-cycle tertiary education students as target groups. Similarly, we did not find evidence of AR applications to teach subjects related to the field of Business, Administration and Law. Hence, given the apparent benefits of the implementation of AR systems in education, future research should consider the development of AR systems focused on those missing target groups and fields of education. Finally, we stress the benefits of implementing AR to promote environmentally responsible behavior. Based on our experiences in the development and subsequent validation of ARtour, we consider that Situated learning is the most accurate learning approach to design AR applications to enhance environmental education. This theory situates learning within authentic activities and contexts, by raising the premise that learning takes place in the same situation in which it is applied. Consequently, the interventions to validate the AR application designed to be applied in environmental education programs should take place in informal environments within actual field trips. Further, our findings indicate that the intervention duration does not influence students' outcomes in environmental education programs. Therefore, to avoid additional expenses, we declare that there is no need to extend the field trips to more than one day.

The main responsibility of policymakers is to take actions that contribute to the success of the implementation of AR in educational environments. Although the potential effectiveness of the use of AR in education has been widely proven, policymakers must act regarding important aspects that can potentially hazard the success of AR experiences. In this regard, the findings in this thesis offer a reference for policymakers, who must make critical decisions regarding funding and educational politics. First, a reported challenge of using AR technologies in some educational institutions is related to poor or non-existent technological infrastructure to support AR services. This affects accessibility, which could hinder teachers' decision to integrate this technology into their classes. Thus, we stress the importance of ensuring quality resources such as Wi-Fi connections, that allow deploying AR technologies with no restriction. Additionally, it is recommended to implement strategies such as Bring Your Own Devices (BYOD) to cope with the lack of mobile devices in some educational institutions. BYOD refers to the policy of permitting students to bring their own mobile devices to the educational institution. This strategy will potentially increase the possibilities of a successful implementation of AR experiences without an increase in institutional expenses. Second, the existing literature shows that some teachers feel that using these technologies could be an element of distraction rather than a learning strategy. This negatively influences teachers' conceptions of this specific technology, which affects their motivation to use AR applications. In this regard, policymakers might encourage teachers by promoting special rewards to teachers who implement these innovative educational practices. However, the key to achieving the paradigm shift is to improve teachers' literacy by providing specific training on AR technologies. This will be reflected in teachers' attitude about AR and will influence in students learning success.

6.2 Limitations of the study and future work

This thesis aimed at describing the state of the art of AR applications for education and the implications of the pedagogical characteristics of AR interventions. However, future research is needed to close some research gaps and identify further possibilities of AR applications in educational settings. Below, we list some of the research gaps that were identified in this work, which may represent a guide for stakeholders for future research.

- The duration of most AR interventions is inferior to one month. This leads us to pose the possibility that the positive impact of AR on education found in this, and in previous studies may obey to a "novelty effect". Therefore, we highlight the need for longitudinal studies that identify changes in long-term memory to corroborate that students effectively appropriate knowledge.

- Software developers should engage in the solution of technical difficulties of AR pedagogical tools to facilitate their usage, especially for people with low technological skills and people with disabilities.
- In line with the previous point, we highlight the need to develop accessible authoring tools to allow people with disabilities and low technological abilities, to become not only consumers but also producers of accessible AR educational applications.
- We also encourage developers to develop and provide software components (assets) that can be reused in different contexts to facilitate the creation of new AR educational applications.
- We based the analysis of the pedagogical approaches on the five approaches derived from constructivism that were identified in the empirical studies of our sample. Therefore, our conclusions are not definitive considering that the range of options of pedagogical approaches is significantly broader. Consequently, we encourage researchers to explore different pedagogical approaches that will potentially benefit AR interventions.
- This study analyzed the moderating effect of some variables that have been identified as important in this study and in previous studies. However, future work should include other variables that are important, to find other benefits of the implementation of AR systems in education such as type of augmentation, spatial competence, and attitudes toward technology. The analysis of these variables is important to understand the impact of AR on education and, therefore, we encourage researchers and practitioners to consider them for future research.
- Finally, we encourage stakeholders to begin exploring the possibilities of the third generation of AR in education. This generation has been described to be characterized not only by mobile AR but also by WebAr-based applications and stand-alone headsets such as HoloLens, Oculus Rift, and iGlass. Hence, developers have the opportunity to become pioneers in the design of the new generation of devices that will create a renewed paradigm for AR in education.

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PART II

INDIVIDUAL STUDIES

This section presents the eight individual studies that resulted from the research work done during the course of the thesis. Five of the studies correspond to qualitative and/or quantitative analysis of previous empirical studies on AR in education and three correspond to the description of the development and subsequent validation of ARtour. Four of the studies were published as journal papers, three studies were published as conference proceedings papers, and one study was published as journal abstract. It is important to mention that I am the main author of all the contributions described in this thesis, both the research papers and the educational application.

7. Systematic review and meta-analysis of Augmented Reality in educational settings

Reference:

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3.634 (Q1)	7.1 (Q1)	22	0.954 (Q1)

Summary:

Our first specific objective proposes to establish the state of the art of AR technology in education. Particularly, we sought to identify 1) the trends of AR in education, 2) the most common target groups and fields of education, 3) the advantages and disadvantages reported by previous studies, and 4) the inclusion of special needs of users. To answer these issues, we conducted a systematic literature review of 61 studies published between 2012 and 2018 in scientific journals and conference proceedings.

The literature review included three stages: planning the review, conducting the review, and reporting the review. The first stage involved the definition of the strategy to identify the most relevant literature to answer the research questions. In the second stage two of the researchers proceeded to read each paper individually and extract the relevant data in a specific data extraction form. Finally, in the third stage we analyzed, synthesized, and presented the most relevant information that answered the research questions previously established in the planning the review stage.

As a result, the study identified that AR applications for education have been increasing since 2010. The most common target group was *Primary education* although with no significant differences with respect to *Secondary education* and *Bachelor level*. Regarding the broad field of education, the most common field was *Natural sciences, mathematics and statistics*. Furthermore, the study identified that the most reported advantages of AR in education are learning gains and motivation. Only one of the studies included accessibility characteristics, which indicates that most AR applications do not consider the special needs of users. Finally, the study discussed the implications of the results and proposed a route for the stakeholders to guarantee the right inclusion of AR systems in educational scenarios.

Virtual Reality
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S.I. : VR IN EDUCATION

Systematic review and meta-analysis of augmented reality in educational settings

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Abstract

Augmented reality (AR) is an important technology to enhance learning experiences. Many studies have been conducted to establish the tendencies, affordances and challenges of this technology in educational settings. However, these studies have little analyzed important issues such as the special needs of specific users or the impact of AR on education through the quantitative analysis of the data. This paper presents a literature review that covers 61 studies published between 2012 and 2018 in scientific journals and conference proceedings. As a result, it identifies the status and tendencies in the usage of AR in education, the impact of this technology on learning processes, open questions as well as opportunities and challenges for developers and practitioners. The results indicate that AR has a medium effect on learning effectiveness ($d = .64$, $p < .001$). The most reported advantages of AR systems in education are "learning gains" and "motivation." Otherwise, it is also important to mention that only one of the AR systems of the studies includes *accessibility features*, which represents a setback in terms of social inclusion. Therefore, given the apparent multiple benefits of using AR systems in educational settings, stakeholders have great opportunities to develop new and better systems that benefit all learners. This technology covers a wide range of topics, target groups, academic levels and more. This could be an indicator that AR is achieving maturity and has successfully taken root in educational settings.

Keywords Augmented reality · Education · Inclusive learning · Information technologies · Literature review · Meta-analysis

1 Introduction

Augmented reality (AR) is an important technology that combines reality with virtuality (Akçayir and Akçayir 2017; Azuma 1997). Teachers, engineers, researchers and practitioners are developing different tools and methodologies that include this technology, to benefit students and teachers by enriching the learning and teaching experiences. However, as reported by Wu et al. (2013), studies related to AR remain immature compared to studies of other technologies in education.

Since Tom Caudell coined the term augmented reality in the early 1990s (Lee 2012), this technology has experienced a rapid growth. This growth has accelerated from 2010 due probably to improvements in mobile computing power and functionality, which has led to AR systems being integrated into mobile devices making this technology available to a greater number of users (Bower et al. 2014). Augmented reality has a wide variety of fields of applications such as medicine, tourism, entertainment and education (Akçayir and Akçayir 2017). Sometimes it is confused with virtual reality (VR), but while VR immerses the user in a totally virtual environment, AR is rather a blending between virtuality and reality (Carmigniani et al. 2011).

In education, AR has been used to design pedagogical tools to enrich learning and teaching experiences (Garzón et al. 2017). Many studies indicate that AR technologies allow students to acquire knowledge in a more significant

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way, helping them to develop special skills that are much more difficult to obtain with other pedagogical resources (Akçayir and Akçayir 2017; Cheng and Tsai 2013; Safar 2017). For example, AR provides the learner easy access to unobservable phenomena such as the movement of the sun in simulated classroom contexts (Tarng et al. 2018), or the behavior of magnetic fields (Cai et al. 2017), among others, which have been identified by teachers and previous research as troublesome for students.

Nevertheless, as a developing technology, AR has barriers to overcome such as usability (Akçayir et al. 2016), resistance from teachers (Lee 2012) and overload of information (Akçayir and Akçayir 2017; Turan et al. 2018). There are also technical issues such as difficulties in detecting user's location (Palmarini et al. 2018) specially indoors, and limitations in pattern recognition that affect the ergonomics applications (Fraga-Lamas et al. 2018).

This systematic review seeks to increase the literature on the implications of the use of AR in education by answering the following research questions:

- RQ1 What are the trends of augmented reality?
- RQ2 What is the most common field of education for augmented reality applications?
- RQ3 Have these applications considered special needs of particular users?
- RQ4 What are the advantages of using augmented reality in educational environments?
- RQ5 What are the disadvantages and challenges of using augmented reality in educational environments?
- RQ6 What is the impact of augmented reality on learning effectiveness of students?

To present AR trends in education (RQ1), we consider two aspects. First, we present the evolution over time regarding the number of publications in journals and conference proceedings. Then, we identify the levels of education in which AR is most applied. Concerning the fields of education (RQ2), we use the broad fields of education proposed by the International Standard Classification of Education ISCED (UNESCO 2011) to identify the domain of the applications of AR involved in the selected studies. This study interprets special needs of users (RQ3), as physical disabilities (deafness, blindness, etc.) and mental disabilities (learning difficulties, attention deficit disorder, etc.). Advantages of using AR in educational settings (RQ4) refer to positive outcomes and attitudes of students when using AR systems (academic level improvement, motivation, creativity, autonomy, etc.). In contrast, disadvantages of using AR in educational settings (RQ5) have to do with negative impact of AR systems on students (complexity, technical aspects, multitasking, etc.). Finally, we conducted a meta-analysis to investigate the impact of AR on learning effectiveness of students (RQ6). Learning gain was used as the dependent variable to measure learning effectiveness. This gain is defined as the improvement in student scores between the beginning and the end of the intervention through AR applications. This improvement was assessed based on Cohen's *d* effect size for quantitative studies. The effect size is defined as a quantitative reflection of the magnitude of some phenomenon that is used to address a question of interest (Hedges and Olkin 2014; Kelley and Preacher 2012). The effect size is commonly used to quantify the effectiveness of an intervention, in the present case, the effectiveness of AR systems in educational environments regarding students' learning gains.

The remainder of this paper is structured as follows: Sect. 2 discusses related previous studies. Section 3 presents the process carried out to develop the search, which includes an explanation of the work performed in each of the three stages (planning the review, conducting the review and reporting the review). Section 4 presents the most relevant findings of the systematic review to answer the research questions. Section 5 discusses the meaning of the findings, and finally, Sect. 6 concludes the paper and proposes possible routes for future research.

2 Related work

Many studies aim to define the state of the art of AR in relation to education. These studies allow researchers to know the trends, the benefits and the limitations of this technology in education and give a starting point to new developments. Table 1 summarizes some systematic review studies, on issues related to the application of AR in educational settings.

In addition to these, other studies have defined, after a systematic literature review, the status, trends, advantages and challenges of AR in educational scenarios (Antonioli et al. 2014 ; Chen et al. 2017; Mekni and Lemieux 2014; Radu 2014; Wu et al. 2013). However, these studies do not offer answers to issues like special needs of users or disadvantages of using AR systems in educational settings. Hence, with this systematic review, we want to enhance the literature and provide some directions for future research.

3 Methods

This study follows the guidelines proposed by Kitchenham and Charters (2007), who suggests that systematic reviews involve three main stages: planning, conducting and reporting the review.

Table 1 Summary of some systematic reviews related to the usage of AR in educational environments

Study	Review purpose	Studies reviewed	Main findings
Bacca et al. (2014a, b)	This review analyzed studies published between 2003 and 2013 from six indexed journals. It is focused on uses, advantages, limitations, effectiveness, challenges and features of AR in educational environments	32	There is an increase in the number of published studies in the last four years. Most applications of AR are related to Natural Sciences and Humanities and Arts. The most reported advantages of using AR in education are learning gains, motivation, interaction and collaboration
Diegmann et al. (2015)	This reviewed focused on empirical studies to analyze the benefits of using AR in comparison with other conventional learning tools	25	The most reported advantage of using AR in education is the improved learning curve. That is, students learn faster and easier with AR applications compared to non-AR applications. The reduction in the cost of AR technologies has helped to spread its use in educational environments
Tekedere and Göker (2016)	This study conducted a meta-analysis focused on AR applications for education in order to establish a new point of view for future research. The analysis covers the period between 2005 and 2015.	15	The use of AR applications for education has increased in the last five years. The meta-analysis indicated an average effect size of $d = .67$ that corresponds to "medium" effect. This may indicate that application of AR technologies in education has positive effects on students.
Akçayir and Akçayir (2017)	This review analyzed studies published between 2011 and 2016. It is focused on year, learner type, advantages and challenges of AR in educational environments	68	There is an increase in the number of published studies in the last four years. The most reported advantage in the studies is that it promotes enhanced learning achievements

3.1 Planning the review

This stage involved the definition of the strategy to identify the most relevant literature to answer the research questions. We accomplished an iterative double check focused on scientific journals indexed in the Social Sciences Citation Index (SSCI) database, and conference proceedings indexed in the Conference Proceedings Citation Index-Science (CPCI-S) database. We used the Web of Science (WoS) site to perform the search.

We used the search terms "Augmented Reality AND Education," "Augmenting Reality AND Education" and "Mixed Reality AND Education." The search parameters were set as follows: Document type: "Article." Language: English. The first search allowed us to find 635 articles. Then, we established categories: "Education & Educational Research," "Education, Scientific Disciplines" and "Computer Science Interdisciplinary Applications." After these new filters, we found 345 articles.

These articles were carefully read by two of the researchers to identify the suitability of each article for the study. Articles that did not accomplish the inclusion and exclusion criteria (see Sect. 3.1.1) were discarded. Finally, 61 studies were identified as relevant to the purpose of this review.

3.1.1 Inclusion and exclusion criteria

Papers selected for the systematic review satisfied the following criteria:

- Studies related to the research questions
- Studies that include case studies
- Studies that followed a qualified peer-review process
- Studies must consist of pretest and posttest design (for the meta-analysis)
- Studies must consist of experimental and control groups (for the meta-analysis)

Since the systematic review focused on educational settings, we excluded papers which, despite meeting all the prior criteria, were not focused on education. The flowchart of the systematic review is shown in Fig. 1.

3.2 Conducting the review

This stage took place once the phase of *planning the review* was completed. We designed a data extraction form (spreadsheet document) with the following elements: study name, year of publication, journal of publication, sample size, target group, field of education, reported advantages, reported disadvantages, time dimension and main findings. Two of the researchers proceeded to read each paper individually and to extract the relevant data. Cohen's kappa statistic was

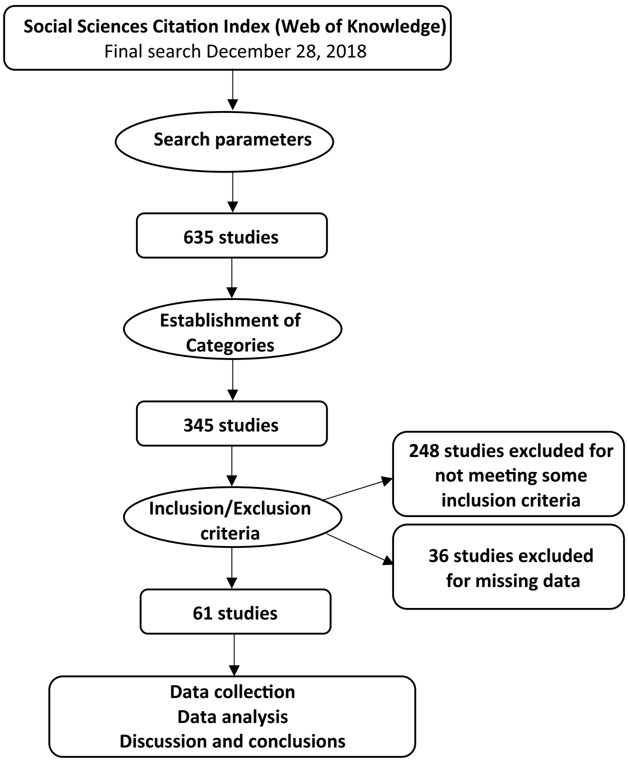

Fig. 1 Flowchart of the systematic review

used to measure intercoder reliability. This value was found to be 0.94, which corresponds to almost perfect agreement as stated by Cohen (1968). Occasional disagreements were discussed and resolved by consensus.

3.3 Reporting the review

In this stage, we analyzed, synthesized and presented the most relevant information that answered the research questions previously established in the planning stage. The results of the study are summarized in the *Findings* section.

3.4 Meta-analysis

We conducted a meta-analysis to measure the learning gains of students when they use AR systems. Glass (1976, p. 3) defined meta-analysis as "the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating findings." Our meta-analysis included 27 pretest–posttest control (PPC) design studies. In this research design, students are assigned to experimental and control groups, and each student is evaluated before and after the treatment (Morris and DeShon 2002). The PPC design provides a more effective framework to estimate the treatment effects compared to studies with only posttest measures or with no control group. Therefore, we did not take into account other research design studies for the meta-analysis.

In addition, *level of education* and *field of education* were defined as the independent variables. The effect size per level of education indicates how each target group benefits from AR systems. Similarly, the effect size per field of education indicates how each domain subject benefits from AR systems.

Learning gains were assessed based on Cohen's *d* effect size. To calculate the *d* value, we used the effect size estimate recommended by Morris (2008). This estimate was calculated using Eq. (1) and allowed us to obtain an unbiased estimate of the population effect size.

$$d = \frac{\left(M_{\text{POST-E}} - M_{\text{PRE-E}}\right) - \left(M_{\text{POST-C}} - M_{\text{PRE-C}}\right)}{\text{SD}_{\text{PRE}}} * C_{\text{P}} \quad (1)$$

$M_{\text{POST-E}}$ and $M_{\text{PRE-E}}$ are the mean scores of the experimental groups for the posttest and pretest. $M_{\text{POST-C}}$ and $M_{\text{PRE-C}}$ are the mean scores of the control groups for the posttest and pretest. SD_{PRE} is the pooled standard deviation and was calculated using Eq. (2). Finally, C_{p} is the bias correction and was calculated using Eq. (3).

$$\text{SD}_{\text{PRE}} = \sqrt{\frac{\left(N_{\text{E}} - 1\right)\text{SD}^2_{\text{PRE-E}} + \left(N_{\text{C}} - 1\right)\text{SD}^2_{\text{PRE-C}}}{\left(N_{\text{E}} + N_{\text{C}} - 2\right)}} \quad (2)$$

N_{E} and N_{C} are the sample sizes of the experimental and control groups. $\text{SD}_{\text{PRE-E}}$ and $\text{SD}_{\text{PRE-C}}$ are the standard deviations of experimental and control groups for the pretest.

$$C_{\text{P}} = 1 - \frac{3}{4\left(N_{\text{E}} + N_{\text{C}} - 2\right) - 1} \quad (3)$$

To interpret the effect size values, we used the following classification: $d = .2$ (small effect), $d = .5$ (medium effect), $d = .8$ (large effect) (Cohen 1992), $d = 1.20$ (very large effect) and $d = 2.0$ (huge effect) (Sawilowsky 2009).

4 Findings

4.1 Trends of augmented reality

This subsection presents the trends of AR taking into account two aspects. First, we present the evolution over time regarding the number of publications in journals and conference proceedings. Then, we identify the levels of education in which AR is most applied.

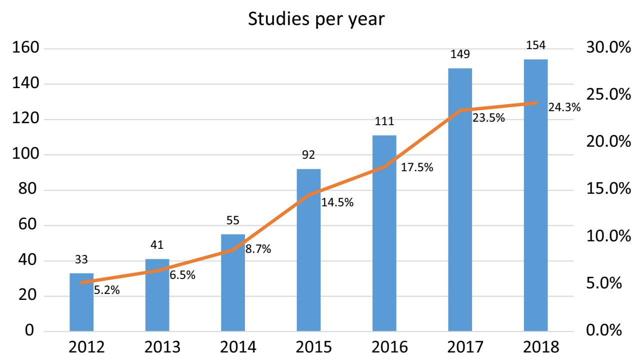

Fig. 2 Studies related to the application of AR in education per year (WoS)

4.1.1 Evolution over time

Of the 61 studies selected for the literature review, 4 studies were published in 2012 (6.67%), 9 in 2013 (15%), 12 in 2014 (20%), 13 in 2015 (21.67%), 12 in 2016 (20%), 8 in 2017 (11.67%) and 3 in 2018 (5%). However, these percentages do not represent the total amount of studies published every year. In order to identify the actual evolution over time concerning the application of AR systems in educational settings, we used the initial results of the search. Figure 2 shows the distribution per year of the 635 articles from 2012 to 2018.

The search indicates that, as previous studies have stated (Akçayir and Akçayir 2017; Bacca et al. 2014a, b), the number of published studies is increasing year after.

4.1.2 Education level

Educational level refers to the educational stage of the target groups that participated in each study. To identify this, we used the International Standard Classification of Education (UNESCO 2011) of the United Nations. The distribution is rather consistent for children (*Early childhood education* and *Primary education*), teenagers (*Lower secondary education* and *Upper secondary education*) and *Bachelor's or equivalent level*. *Post-secondary non-tertiary education* was not considered as a target group in any of the selected studies. This level of education corresponds to vocational education and training (VET) and is composed of students that have completed secondary education (or most of it) and want to be prepared for a specific labor without enrolling to a university. There is evidence that students in these groups lack motivation, concentration, attention, among others (Bacca et al. 2015), which are some of the main advantages that AR systems can offer as stated in Sect. 4.4. Two studies correspond to the category *Not elsewhere classified*. It refers to studies that did not contemplate any specific target group but use a mixture of participants (different ages) to validate the AR application. None of the selected studies had postgraduate students (Master or PhD degrees) as a target group. Table 2 shows the percentages of application of AR systems by target group.

4.2 Education field

Concerning education fields, we used the broad fields proposed by the International Standard Classification of Education ISCED (UNESCO 2011) in order to identify the domain of the applications of AR involved in the selected studies. As was expected, data collected show that most uses of AR in education are related to the broad field of *Natural sciences, mathematics and statistics*. It supports the findings reported in prior researches by Bacca et al. (2014a, b) and Blake and Butcher-Green (2009), and has to do probably with the advantages that AR provides when teaching *Abstract concepts* as demonstrated by Ibáñez et al. (2014).

Augmented reality applications related to *Arts and humanities* are almost exclusively oriented to the narrow field of *Arts*. This is one of the most common educational fields reported in the selected studies. Augmented reality may represent a new way to utter the talents of the artists since it helps to explore audiovisual techniques in a deeper way (Wei et al. 2015). Nevertheless, most uses of AR in *Arts and humanities* are the various museums applications that can be found worldwide. This technology brings art collections to life and allows rich media content such as images, video, and 3D environments and animations to be layered over real environments or objects (Chang et al. 2015).

Applications related to *Social sciences, journalism and information* are focused on psychology, and none is related to journalism or information. All the applications related to the field of *Engineering, manufacturing and construction* are focused on engineering. Even though the study reports one study related to the application of AR in subjects related to *Education,* there is still a lot to develop in this field.

Table 2 Percentage of studies analyzed per target group

Target group	Number of studies	Percentage (%)
Early childhood education	1	1.6
Primary education	19	31.1
Lower secondary education	11	18.0
Upper secondary education	9	14.8
Post-secondary non-tertiary education	0	0.0
Short-cycle tertiary education	1	1.6
Bachelor's or equivalent level	18	29.5
Master's or equivalent level	0	0.0
Doctoral or equivalent level	0	0.0
Not elsewhere classified	2	3.3

Table 3 Percentage of studies analyzed per education field

Broad field	Number of studies	Percentage (%)
Natural sciences, mathematics and statistics	30	49.2
Arts and humanities	10	16.4
Social sciences, journalism and information	7	11.5
Information and communication technologies	5	8.2
Engineering, manufacturing and construction	4	6.6
Health and welfare	4	6.6
Education	1	1.6
Business, administration and law	0	0.0
Agriculture, forestry, fisheries and veterinary	0	0.0
Services	0	0.0

We could not find any evidence of using AR in the broad fields of *Business, administration and law; Agriculture, forestry, fisheries and veterinary;* and *Services*. Therefore, innovative researchers have opportunities to develop applications that support the learning of these topics. Table 3 presents the percentages of usage of AR by broad field of education.

4.3 Consideration of special needs of the users

Schmitz et al. (2015) presented "HeartRun." This is a cardiopulmonary resuscitation (CPR) training approach for school kids that includes aids for blind and visually impaired people, as well as for children with learning disabilities. This is the only study that considers special needs of users among those selected for this study. Thus, just 2.5% of the studies included applications that contain features that address special needs of users.

This finding seems to validate the results of Bacca et al. (2014a, b) and Wu et al. (2013) who pointed out that only a few systems have been designed for users with special needs and disabilities. We emphasize the need for further research to recognize diversity in educational settings and address diversity using AR applications. Hence, it is important that stakeholders begin to take into account the criteria provided by the Web Accessibility Initiative (WAI) in the mobile accessibility guideline (WAI 2016), as well as the Global Public Inclusive Infrastructure (GPII) proposed by Vanderheiden and Treviranus (2011).

4.4 Advantages of using augmented reality in educational environments

A hundred percent of the selected studies reported some kind of advantage when using AR systems in education. Table 4 summarizes the advantages reported in the 61 selected studies. It is important to clarify that these are only some of the advantages more commonly reported in the studies. Likewise, most studies reported more than one advantage.

Learning gain is the most common reported advantage. Studies stated that, when using AR systems, students improve their academic performance. This improvement was reported not only by data, but also for different teachers and the students themselves. Among others, Chang et al. (2013) mentioned an academic activity held in South Korea, which focused on the integration of AR to assist students learning of socio-scientific issues. They demonstrated that students guided through AR obtained better scores than those who were guided through traditional approaches.

Motivation is the second most common reported advantage. Studies informed that the students felt more motivated by using AR applications, compared to other pedagogical tools. A comparative review of the impact of using AR in educational settings carried out by Radu (2012) shows that the use of AR increases the motivation in the students, who expressed they had fun while learning and were willing to repeat the AR experience. Likewise, a study conducted at a middle school in Madrid by Di Serio et al. (2013) demonstrated through qualitative and quantitative data that the inclusion of AR was a motivation factor when it was integrated into the learning environments. This motivation may be a direct consequence of another very important advantage reported in the selected studies: *Sensory engagement*. Roberto et al. (2011) expressed that *Sensory engagement* "is related to how children learn in their natural mode, using several of their senses in a constructive process." Namely, activating multiple senses in the learners' brain improves knowledge retention (Cheng and Tsai 2013) which is a great advantage in the learning process.

Table 4 Percentage of studies analyzed per reported advantages

Advantages	Number of studies	Percentage (%)
Learning gains	51	83.6
Motivation	46	75.4
Abstract concepts	16	26.2
Autonomy	16	26.2
Sensory engagement	14	23.0
Memory retention	9	14.8
Collaboration	8	13.1
Creativity	4	6.6
Accessibility	3	4.9

Another common advantage reported in the selected studies when using AR has to do with the possibility of facilitating the comprehension of *Abstract Concepts* (Akçayir et al. 2016; Chang et al. 2013; Lin et al. 2013). Studies mentioned that AR is ideal to explain things that cannot be observed. Ibáñez et al. (2014) presented the results of a study in which they compared an AR-based application with its equivalent web-based application to learn the basic concepts of electromagnetism. They obtained consistent evidence that suggests that AR-based applications contribute to increase academic achievement in a more efficient way compared to traditional web applications.

Memory retention has been also reported as an advantage of using AR in educational settings. This technology not only helps retain knowledge, but also gives the student the possibility of retaining it for longer periods of time compared to other pedagogical methodologies (Chiang et al. 2014; Sommerauer and Müller 2014; Zhang et al. 2014). Santos et al. (2014) analyzed 87 research articles on AR learning experiences. They concluded that AR provides three important elements: real-world annotation, contextual visualizations, and vision-haptic visualizations, which favor the long-term memory in the human brain.

Autonomy is other important advantage described in the selected studies. The combination of real and virtual worlds increases the autonomy of students taking into account their natural abilities and motivation for using technological devices (Ferrer-Torregrosa et al. 2015; Ibáñez et al. 2014).

Collaboration was also signaled as a major advantage. Augmented reality creates possibilities for collaborative learning around virtual content (Bujak et al. 2013) which can facilitate learning, since it allows learners to interact with their partners, as well as with the educational content. *Accessibility* and *Creativity* are other advantages described in the selected studies. The aforementioned advantages can be an indicator of the numerous benefits that can be obtained when using AR in educational settings.

4.5 Disadvantages of using augmented reality in educational environments

Fifteen percent of the selected studies reported some disadvantages or problems when using AR in educational settings. Table 5 summarizes the main disadvantages reported in the selected studies.

The most reported disadvantage refers to the *Complexity* of using AR especially when applied to children. Being a novel technology, which involves multiple senses, becomes sometimes a very complex tool especially for those who do not have technological abilities (Herpich et al. 2014).

Teachers participating in some studies manifested having *Technical difficulties* when using AR in their classrooms. This may be caused by the scarce technical training from part of some teachers to manage the AR systems, which could limit their use in educational environments. Another reported issue related to AR systems is *Multitasking*. As Radu (2012) indicated, students expressed that AR applications demand too much attention, which can be a distraction factor. This can cause students to ignore instructions or important stages of the experience.

Table 5 Percentage of studies analyzed per reported disadvantages

Disadvantages	Number of studies	Percentage (%)
Complexity	6	9.5
Technical difficulties	5	7.9
Multitasking	4	6.3
Resistance from teachers	2	3.2

Finally, *Resistance from teachers* has been reported as a possible difficult of the implementation of AR in educational environments. Some teachers may prefer having total control over content, despite recognizing the benefits of using AR applications (Wu et al. 2013).

4.6 Impact of augmented reality on learning effectiveness of student

To identify the impact of AR on students learning effectiveness, we calculated the Cohen's d effect size of each quantitative study using the means and standard deviations for experimental and control groups. When a study reported several mean scores and standard deviations, they were averaged, and the averages were used to calculate the effect size (Bernard et al. 2004). Table 6 shows the studies that were considered for the meta-analysis.

The mean effect size calculated from the studies was $d = .64$ with a 95% confidence interval of .55–.74. This value corresponds to a medium effect as indicated by Cohen, which supposes that AR has a positive impact on learning gains. We assessed heterogeneity tests Q and I^2, to validate the use of a random-effects model. The Q statistic was proposed by Cochran (1954) and represents the amount of heterogeneity among the studies. Under the hypothesis of homogeneity, the Q statistic follows a Chi-square distribution with $k - 1$ degrees of freedom (k, number of studies). The Q value in this study was greater than the critical value (χ^2) according to the Chi-square distribution (Lancaster and Seneta 2005), which indicates heterogeneity among the studies (see Table 7). However, Q statistic does not report the extent of heterogeneity, only its statistical significance. To overcome this limitation of the Q test, Higgins and Thompson (2002) proposed the I^2 index. This index measures the extent of heterogeneity dividing the difference between the Q value and its degrees of freedom by the Q value itself,

Table 6 Studies analyzed in the meta-analysis

References	N	Experimental				Control			
		M_{PRE}	S_{PRE}	M_{POST}	S_{POST}	M_{PRE}	S_{PRE}	M_{POST}	S_{POST}
Chen and Tsai (2012)[a]	116	–	–	–	–	–	–	–	–
Hsiao et al. (2012)[a]	482	–	–	–	–	–	–	–	–
Cai et al. (2013)	50	67.42	19.19	80.42	15.46	67.65	15.84	78.69	13.94
Hsiao (2013)[a]	66	–	–	–	–	–	–	–	–
Chang et al. (2014)	135	57.68	14.14	71.01	12.75	59.04	15.91	58.09	12.23
Zhang et al. (2014)	74	5.93	3.21	8.04	3.05	5.98	3.21	6.70	3.70
Sommerauer and Müller (2014)	101	1.75	1.11	3.64	1.31	1.81	1.16	2.59	1.28
Ibáñez et al. (2014)	64	3.25	1.17	6.11	1.40	3.38	1.10	5.00	1.87
Jee et al. (2014)[a]	142	–	–	–	–	–	–	–	–
Chang et al. (2015)	55	39.41	9.66	65.84	11.82	43.33	11.68	55.31	11.64
Barma et al. (2015)	150	4.90	1.20	6.20	1.11	5.08	1.37	5.95	1.25
Tarng et al. (2015)	60	52.8	13.50	77.50	11.00	53.2	17.1	69.3	12.3
Ibanez et al. (2016)	82	5.21	2.19	6.31	1.63	4.55	2.01	4.92	2.12
Chen et al. (2016)	71	86.33	7.78	71.89	14.56	83.83	11.73	62.69	15.23
Akçayir et al. (2016)	76	1.99	0.68	3.22	0.51	2.24	0.59	2.93	0.52
Juan et al. (2016)	38	7.54	2.00	9.00	1.56	8.23	1.43	9.6	0.72
Tarng et al. (2016)	56	40.89	13.83	48.44	14.09	38.62	16.81	39.17	17.9
Cai et al. (2017)	42	25.95	6.36	42.50	7.63	25.95	6.99	40.38	8.50
Mumtaz et al. (2017)	45	108.74	17.26	136.27	18.45	98	13.56	114.32	19.03
Joo-Nagata et al. (2017)	143	5.04	2.38	13.57	3.88	5.23	2.19	11.08	4.22
(Wang 2017)	103	3.87	0.85	4.23	0.85	3.62	0.85	3.65	0.79
Tosik Gün and Atasoy (2017)	88	12	4.88	15.43	5.11	12.46	3.98	14.5	4.83
Calle-Bustos et al. (2017)	70	1.95	0.48	7.45	1.34	2.50	0.67	6.86	1.44
Liou et al. (2017)	27	22.15	8.78	73.55	10.781	21.15	8.08	64.76	16.76
Karagozlu (2018)	147	19.10	7.51	79.11	11.721	19.35	9.25	53.99	16.58
Tarng et al. (2018)	56	38.39	7.77	85.36	10.54	40.18	7.73	78.75	7.89
Medina et al. (2018)	18	53.33	19.44	95.56	6.85	48.89	25.58	84.00	15.54

M_{PRE} and M_{POST} are the mean scores of the pretests and posttests for experimental and control groups. S_{PRE} and S_{POST} are the standard deviations of the pretests and posttests for experimental and control groups

[a]Indicates papers that did not provide mean scores and standard deviations, but, instead, provided effect size values

Table 7 Summary of meta-analysis results

Variable	Value
Number of samples (K)	27
Total sample size (N)	2557
Effect size (d)	0.64
p (d)	< .001
Heterogeneity test (Q)	55.00
Critical value (χ^2)	40.113
I^2	52.72
Z	13.16
95% Lower limit	0.55
95% Higher limit	0.74

all multiplied by 100. The I^2 index can be interpreted as the percentage of the variability between the studies due to heterogeneity. The I^2 value found in this meta-analysis ($I^2 = 52.72$) indicates a medium heterogeneity as suggested by Huedo-Medina et al. (2006). Additionally, a probability value (p) lower than 0.01 leads us to reject the null hypothesis of homogeneity and accept the alternate hypothesis of heterogeneity. These values shown in Table 7 support the assumption of the random-effects model (Borenstein et al. 2010).

4.6.1 Effect size per level of education

To identify the effectiveness of AR per level of education, we calculated the average effect size for each educational stage. Having into account that the number of quantitative studies in the meta-analysis is relatively small, the number of studies per target groups is also small. For this analysis, only the target groups that participated in the quantitative studies were taken into account. Data analysis indicates that there are no significant differences according to the level of education. The effect size values found indicate that AR has a medium impact on each of the four levels of education that were considered for this meta-analysis. Table 8 summarizes the meta-analysis per level of education.

4.6.2 Effect size per broad field of education

To identify the effectiveness of AR per subject, we calculated the average effect size for each broad field of education. Taking into account that the number of studies is relatively small, the number of studies per broad field is also small. For this analysis, only the broad fields of education reported in the quantitative studies were taken into account. Analysis indicates that AR has a large effect on learning *Arts and humanities* and Health and welfare. Likewise, results show a medium effect on learning *Social sciences, journalism and information* and *Natural sciences mathematics and statistics*. Finally, results indicate a small to medium effect on learning *Health and welfare* and a small effect on learning *Education*. Table 9 summarizes the meta-analysis per broad field of education.

Table 8 Summary of meta-analysis per level of education

Variable	Primary education	Lower secondary education	Upper secondary education	Bachelor or equivalent level
K	9	5	5	8
N	596	562	723	676
d	.65	.60	.70	.62
p (*d*)	< .01	< .01	< .01	< .01
Z	6.98	4.12	6.90	6.62

5 Discussion

The results of the systematic review seem to indicate that AR is an important technology that may be reaching maturity. We can notice that AR applications are present not only in education but also in medicine, tourism, industry, entertainment, among others (Eishita and Stanley 2018; Fraga-Lamas et al. 2018; Rojas-Muñoz et al. 2018; Yim et al. 2017)

The integration of AR systems in mobile devices has led that along with the spread of those devices (Statista 2015), the development and use of AR technologies are increasing worldwide. This may be one of the causes of the steady increase in the number of publications since 2010 identified by this and other studies (Akçayir et al. 2016; Bacca et al. 2014a, b; Chen et al. 2017; Diegmann et al. 2015). Therefore, it could be concluded that as the use of mobile devices expands, especially in developing countries, the use of AR technologies will also increase.

The most common target group in the selected studies is *Primary education*. Augmented reality systems give students the possibility to learn while playing. This can be very motivating for children, especially to learn unobservable concepts that are difficult to understand (Parhizkar et al. 2012). However, these systems require technological abilities and tend to demand too much attention, which can be a distracting factor that confuses children. Similarly, the second most common target group is *Bachelor or equivalent level.* These groups are usually composed of people between 17 and 24 years old. Namely, they are mature enough to handle the technology, but they frequently need pedagogical aids to acquire knowledge.

The analysis of the data does not show significant differences in effect sizes per level of education. Therefore, the results seem to indicate that the level of education does not moderate the impact of AR on education. However, it is necessary to take into account that the number of studies in some levels of education is too low or inexistent.

Most studies were applied in the broad field of *Natural sciences, mathematics and statistics* which coincides with the results by Bacca et al. (2014a, b) and Chen et al. (2017). These subjects include many *Abstract concepts*

Table 9 Summary of meta-analysis per broad field of education

Variable	Natural sciences mathematics and statistics	Arts and humanities	Social sciences, journalism, and information	Information and communication technologies	Health and welfare	Education
K	15	3	2	3	3	1
N	1544	323	197	203	174	116
d	.69	.96	.71	.36	.81	.27
p (*d*)	< .01	< .01	.02	< .01	< .01	< .01
Z	10.54	6.12	2.13	2.83	3.95	4.12

that are more easily comprehended by the help of AR applications (Cai et al. 2013; Chiu et al. 2015). Oppositely, we could not find evidence of the application of AR in the fields of *Business, administration and law*; *Agriculture, forestry, fisheries and veterinary*; and *Services*. These fields of education could benefit from the apparent multiple benefits of AR systems, which lead us to encourage researchers to explore the possibilities in these areas.

The analysis of the data allowed us to identify that just one single AR application (in the selected studies) includes aids for users with some type of disability. The process of development of AR applications should include engineers (to develop programming), educators (as thematic experts) and other specialists in order to generate qualified educational resources (Cuendet et al. 2013). Similarly, a diverse team should ensure that AR applications include features that enable people with any type of disability to interact with them, considering the special needs and preferences of students and teachers.

Advantages of using AR in educational settings go from psychological to learning aspects. There is convincing evidence of the multiple benefits that this technology can provide to educational scenarios (Akçayir and Akçayir 2017). With respect to previous studies, we found no new reported advantages. *Learning gains* continue to be the most reported advantage of AR systems in education followed by *motivation*. It is important to mention that each new study continues to report multiples benefits that help improve, not only the academic level of students, but also many other personality traits as autonomy, creativity and collaboration. In addition, the fact that AR systems increase students' motivation and academic achievement could eventually reduce the costs associated with grade repetition and early school/college dropout, and the social problems that these events may cause.

Despite the apparent multiple benefits that AR brings to education, this technology has still some difficulties to overcome, such as complexity, technical issues and some resistance from teachers. Fifteen studies reported some kind of disadvantage when using AR systems in educational settings. However, these disadvantages have to do with the fact that this is a developing technology. Hence, it may be concluded that, as this technology advances, most of its problems will be fixed (Bower et al. 2014). Besides, having into account that the benefits of its use seem to be clear, it is worthwhile to continue working and developing strategies to overcome them.

The meta-analysis indicates that AR has a medium effect size on learning effectiveness of students. It is very important, considering that the effect size of educational technology found by two separate studies was found to be $d=0.35$ by Tamim et al. (2011) and $d=0.546$ by Chauhan (2016).

The effect of AR on learning gains was found to be medium on each level of education considered in the analysis. Due to the lack of data, it was not possible to calculate the effect size on *Early childhood education*, *Post-secondary education*, *Short-cycle education*, *Master's level* and *Doctoral level*.

Concerning broad field of education, AR has a large effect size on *Arts and humanities* and *Health and welfare*. Data show a medium effect size on *Social sciences, journalism and information* and *Natural sciences, mathematics and statistics.* The effect was found to be small to medium on *Information and communication technologies* and small *Education.* Due to the lack of data, it was not possible to calculate the effect size on *Engineering, manufacturing and construction, Business, administration and law*; *Agriculture, forestry, fisheries and veterinary*; and *Services*.

6 Limitations of the study

This literature review has some limitations that must be kept in mind for further research. There are some important research questions that might give important information respect to the trends, affordances and challenges of AR systems in education, which were not addressed in this study. For example, this study does not state what are the research groups or institutions that develop AR systems for education. The study does not reveal what are important funding sources for developers and practitioners. The study does not establish what are the technological tools (software development kits) that are used to develop the AR applications. In addition, further research should include the analysis of other moderating variables in order to provide a more complete understanding of the impact of AR on education.

Besides, after the analysis of the data, we do not specify what features should include AR systems to better their accessibility for people with disabilities. We do not propose any possibility of solution for none of the found challenges. Further research needs to be done to give an answer to the aforementioned issues in order to provide other directions and continue to enlarge the knowledge about AR systems for educational environments. Besides, with the intention of ensuring the accuracy of the quantitative information, it is imperative that further research includes bigger samples.

7 Conclusion and future work

This work presents a systematic literature review and meta-analysis of 61 studies focused on AR applications for education. Results seem to indicate that AR is an important technology that may be reaching maturity. We can notice that AR applications are present not only in education but also in medicine, tourism, industry, entertainment, among others. The number of published studies related to applications of AR in education has been steadily increasing since 2010. This must do probably with the integration of AR systems in mobile devices such as smartphones and tablets, which has led that along with the spread of those devices, the development and use of AR technologies are increasing, worldwide. Therefore, it could be concluded that as mobile devices usage spreads, especially in developing countries, the usage of AR technologies will also increase.

With this literature review, it is pretended not only to show the status of AR in education, but also to establish a route for the stakeholders to guarantee the right inclusion of AR systems in educational scenarios. This route includes three main lines of work. First, it is important that governmental institutions, industry and educational institutions increase their inversions in projects focused on the development of AR systems, with the intention of expanding the benefits of this technology. Second, software developers should engage in the solution of technical difficulties of AR pedagogical tools to facilitate their usage, especially for people with low technological skills and people with disabilities. Finally, researchers should continue to conduct more studies to demonstrate the effectiveness of the inclusion of AR systems in teaching–learning processes.

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8. Augmented Reality applications for education: five directions for future research

Reference:

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Summary:

The purpose of our first specific objective was to identify the current state of the art of AR in education to establish what has been done and what is lacking to do. The results of the systematic literature review described in the previous subsection unveiled important findings such as the most common fields of education and levels of education, the advantages and disadvantages of AR applications in educational settings, and the inclusion of accessibility characteristics in AR applications.

Subsequently, in this subsection, we described a study that aimed to propose five directions that developers and practitioners should take around practical solutions for some of the challenges of AR systems for education. The proposed directions have to do with the need of addressing special requirements of users, the opportunities for developing unexplored broad fields of education and unexplored target groups, possible strategies to integrate AR into industry looking to obtain funding for the development of this emerging technology, and finally, indications on how to design pedagogically efficient AR Systems. The study posed that in order to continue improving the possibilities of AR for education, stakeholders and practitioners must continue to address all gaps and develop strategies to solve these and other challenges reported in the previous studies.

Augmented Reality Applications for Education: Five Directions for Future Research

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Abstract. Augmented Reality (AR) systems have reached certain level of maturity in educational environments and their effectiveness has been widely proven. There are many literature review studies that have determined the trends, affordances and challenges of this emerging technology in educational settings. However, these studies do not propose practical solutions that aim to solve the challenges and issues found in AR systems. There are still some problems that need to be addressed in order to obtain the best of this technology and ensure the most appropriate integration of AR into education. There are still unexplored fields of application in which AR systems can help expand the possibilities and improve learning processes. This paper, proposes five directions for future research around possible solutions for some of the most important challenges of AR applications for education. These proposals are based on the findings of a literature review of 50 studies published between 2011 and 2017 in scientific journals. As a result, we provide a guideline for developers and practitioners to continue to expand the accurate integration of AR systems into educational environments.

Keywords: Augmented reality · Special education · Vocational education

1 Introduction

Augmented Reality (AR) technologies, have been studied and developed since the early 60s. However, it was not until 1994 that Milgran and Kishino [1], and then Azuma in 1997 [2], provided accurate definitions of this emerging technology. Prior to 2010, most AR applications were complex and expensive systems that were difficult to access because of their high costs and limited expansion [3]. Although there were some attempts to expand AR systems by creating some applications for education, it was not until the apparition of mobile devices such as smartphones and tablets, that AR systems gained the interest of the research community and expanded around the world along with the usage of mobile devices [4], to become an important tool that has taken root in educational environments.

Augmented Reality systems are present in many fields such as education, medicine, tourism, entertainment, and others [5]. Its efficacy has been widely demonstrated by

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many studies, which have identified a large number of benefits that inclusion of these systems brings to every scenario where it is applied [6].

The integration of AR systems into mobile devices, led to an increase in the number of AR applications in particular as of 2010 [7]. Likewise, the number of studies related to the application of AR systems into education has increased significantly over the past seven years [3]. Most of these studies are based on qualitative and quantitative analysis of case studies, designed to validate an AR application. Moreover, there is large number of literature review studies, which aim to identify the trends, affordances and challenges of AR systems in education.

However, these literature review studies do not offer solutions to those detected challenges. This paper, proposes possible answers to some of the problems that need to be addressed in order to improve the experience of using AR systems in educational settings by suggesting five directions for future research: (1) Design of AR systems that consider special needs of particular users, (2) Integration of AR systems into unexplored fields of education, (3) Inclusion of AR systems into learning processes of unexplored target groups, (4) Integration of AR systems into business and industry, and (5) Design of pedagogically efficient AR systems.

The research was divided into four stages: at first, we selected the studies to be reviewed (including case studies and literature review studies). We then carefully read each study and identified the reported challenges. Third, we classified the challenges according to the five directions of investigation, and finally, we declared possible solutions for those challenges and documented the research.

The five directions for investigation proposed in this study, arose from the analysis of 50 research papers. We conclude that as AR systems continue to mature, most of the challenges that have been found in the studies will be solved and the benefits of their usage in educational environments will expand worldwide, enriching learning and teaching experiences.

The rest of the paper is structured as follows: Sect. 2 presents previous related studies. Section 3 presents the methodology implemented to develop the search. Section 4 presents the five directions of investigation for future research and finally, Sect. 5 concludes the paper.

2 Related Work

As stated before, literature review studies aim to define the trends, affordances and challenges of AR systems in education. As for the trends, these studies show that the number of research papers related to the application of AR in education has steadily increased in the last 6 years [8]. Most common target groups for AR applications are secondary school, Bachelor or equivalent level, and primary school; whilst most applications of AR are related to the broad field of Natural Sciences and Mathematics [9].

With regard to the affordances, these studies have demonstrated that the integration of AR systems into educational settings, brings a large number of benefits including academic performance improvement, attitude toward learning, and cost reduction. The most reported advantage of AR systems for education are “Learning gains” and “Motivation” [8]. Students felt more motivated when they learned using AR systems, which led then to acquire knowledge in a more significant way [10]. Improvement in the academic level of students, eventually reduces the costs associated with grade repetition and school or college dropout [11].

With reference to the challenges, most of these studies declare some limitations of this technology when applied in educational settings. These limitations include unexplored fields of application and unexplored target groups [9], technical difficulties, teacher resistance, and pedagogical issues. Table 1 summarizes the main challenges, problems and limitations of AR systems, reported in some literature review studies.

Table 1. Sumarize of challenges and directions for future research in literature review studies.

Study	Reported challenges	Future research
Carmigniani et al. [5]	Social acceptance. Privacy concerns. Ethical concerns. High costs. Tracking	Continue to monitor the impact of AR on society. Continue to explore how AR can best be applied to expand teaching and learning environments
Radu [12]	Attention tunneling. Usability difficulties. Ineffective classroom integration. Learner differences	Continue to design effective educational AR experiences.
Wu et al. [13]	Technological issues (mainly technical difficulties). Pedagogical issues (teacher resistance, lack of instructional design). Learning issues (cognitive overload)	Applications for unexplored broad fields of education. Use of design models to solve pedagogical issues. Identify curricular and technology characteristics that only AR system can provide
Bacca et al. [9]	Difficulties maintaining superimposed information. Paying too much attention to virtual information. Design for specific knowledge field. Teachers cannot create new learning content	Applications in *Early Childhood* and *Vocational Educational Training* target groups. Applications in the fields of, Health, Education, and Agriculture. Considerations of special needs of students
Diegmann et al. [6]	Every AR application must be designed to a specific context	Considerations of special needs of particular users
Akcayir et al. [3]	Pedagogical issues. Technical problems. Usability issues. Require more time. Not suitable for large groups. Cognitive overload. Ergonomic problems. Difficult to design	Use of design models to solve pedagogical issues. More studies related to the development and usability of AR systems. Considerations of special needs of particular users. More research to discard novelty effect

In addition to these, there are many studies that validated through the qualitative and quantitative analysis of case studies, the effectiveness of specific AR applications in educational settings. However, these studies do not offer possible directions or practical solutions to the challenges encountered. Thus, in this paper, we extract the main challenges reported in 50 studies, group them into categories, and define five directions for future research.

3 Methods

This section describes the process carried out to develop the search. At first, we describe the protocol for selecting the studies to be reviewed. We then explain the process undertaken to extract the data related to the reported challenges. After that, we explain the process of classifying the challenges in order to establish the five directions of investigation for future research.

3.1 Research Protocol

This protocol defines the strategy carried out to develop the search. In order to guarantee the quality of the studies and the updating of the data, we focused our research on scientific papers published in journals indexed in the Social Sciences Citation Index (SSCI) database between 2011 and 2017. We used the key words "Augmented Reality" + "Education" for the search and selected the most cited studies. Papers selected for the study accomplished the following criteria:

- Studies written in English.
- Studies published between 2011 and 2017.
- Studies focused on education.
- Case studies or literature review studies.
- Primary studies published in journals indexed in the SSCI database or the ConferenceProceedings Citation Index (CPCI).
- Studies that have been cited at least once.

Having into account that this research is focused on the challenges reported in scientific studies, we excluded papers that did not report any challenges for AR systems in education.

As a result, we elaborated a list with the 50 most cited papers that satisfied all the inclusion criteria; 40 of the papers corresponds to case studies and 10 to literature review studies. The average citation number received by the selected studies is 58.6. Moreover, all the studies appear in the first 100 results in Google Scholar (sorting by relevance) for the search of the terms "Augmented Reality" + "Education".

3.2 Data Extraction

Once the protocol was agreed, two of the researchers individually read each paper. Content analysis technique was applied to extract the data of each paper. We designed a data extraction form in which we recorded the data extracted from the papers. The document contained the following information: study name, year of publication, sample size, target group, reported disadvantages or challenges, and indications for future research.

3.3 Classification of the Challenges

After completing the data extraction form, we analyzed the reported disadvantages and challenges, and classified them in order to establish five different categories. Separately, we classified the indications for future research (of each paper) into the same five categories. From the analysis of this disadvantages and challenges, we propose the five directions for future research, which are described in the next section.

4 Five Directions of Investigation for Future Research

Although the number of reported disadvantages has decreased significantly by comparing the period of time 2011–2017, AR systems have still some problems to overcome when applied in educational settings. There are some technical and pedagogical specifications that need to be addressed. There are still unexplored target groups and unexplored fields of application of this emerging technology. Therefore, after analyzing the data reported in the selected studies, we proposed five directions of investigation for future research, which aim to solve some of the gaps, and the issues of this technology and thus enhance the affordances of AR for education.

4.1 Design of AR Systems that Consider Special Needs of Particular Users

Among the applications of AR used in the selected studies, just a single one, "HeartRun", includes aids for special needs of particular users [14]. It represents just 2.50% of the selected studies, which is obviously a very low percentage that must increase in order to guarantee access to all type of users. Moreover, some literature review studies have detected this situation, but have not proposed any practical solutions.

Teachers, developers and practitioners must ensure that future AR applications permit any student, regardless of their limitations and taking into account preferences and special needs, to study efficiently using these technologies [15]. Hence, this direction has to do with the need of addressing this significant gap of AR systems. There are some guidelines and standards that stakeholders may use, with the intention of creating *Accessible* AR applications. Next, we describe some of these guidelines and standards.

Ergonomics of Human-System Interaction. The International Organization for Standardization (ISO), provides the Software Ergonomics Standards. These standards establish design principles for multimedia user interfaces, promoting productivity, safety, and health; and outlines practices for improving accessibility.

Ergonomics of human-system interaction (ISO 9241-171:2008), provides ergonomic guidance and specifications for the design of accessible software for use at work, in home, in education and in public places [16]. This standard defines *Accessibility* as "usability of a product, service, environment or facility by people with the widest range of capabilities". This standard is applicable to any interactive system such as AR applications, and promotes the usability of systems for a wider range of users, including handicapped people, elderly people, temporally disable people, and people with cognitive limitations.

Web Content Accessibility Guidelines (WCAG) 2.0. These guidelines cover a wide range of recommendations for making multimedia content more accessible [17]. It is a technical standard (ISO/IEC 40500:2012) that includes 12 guidelines that seek to lead the practitioners to develop content accessible for a wider range of people with disabilities such as blindness, low vision, deafness, hearing loss, learning disabilities, and cognitive limitations. Mobile accessibility is covered by the WCAG and refers to making applications more accessible to people with disabilities when they are using their mobile devices.

The document "Guidance on Applying WCAG 2.0 to Non-Web Information and Communications Technologies (WCAG2ICT)" [18], describes how the WCAG 2.0, can be applied to non-web Information and Communications Technologies under the four principles of accessibility of software: perceivable, operable, understandable, and robust.

Perceivable principle, states that both the information and the components of the user interface must be presented to users so that they can be perceived. Operable principle, states that both, surfing and the components of the user interface must be operable. Understandable principle, states that both, surfing and the components of the user interface must be understandable. Robust principle, states that the content has to be interpreted by different user agents, including assistive technologies.

Universal Design for Learning (UDL). This is a scientifically valid framework for teaching and learning that seeks to address all the user needs and preferences. It helps educators address learner's special needs by suggesting flexible goals, methods, materials and assessments. The main objective of this framework, is to eliminate the barriers existing in curricula giving all learners equal opportunities to learn.

This framework consist of a set of guidelines that can assist anyone who wants to develop any kind of educative material, under three principles based on neuroscience research [19]:

- Principle 1: Provide multiple means of representation.
- Principle 2: Provide multiple means of action and expression.
- Principle 3: Provide multiple means of engagement.

4.2 Integration of AR Systems into Unexplored Fields of Education

Applications of AR systems in educational settings have gained acceptance from educators and learners due to their proven efficacy. This technology has been successfully integrated into many broad fields of education, achieving promising results [20].

Most applications of AR into education in the selected studies correspond to the broad field of *Natural Sciences, Mathematics and Statistics* (52.50%). *Social Sciences, journalism and information* (15%), *Arts and Humanities* (15%), and *Engineering,* *manufacturing and construction* (15%), are other common broad fields where AR is applied. Although there are no applications related to the broad field of *Health* among the selected studies, that is another important field of application of AR systems [21].

In contrast, there are fields of education where AR has not been applied, or at least, there is no evidence in the scientific literature. There are two broad fields of education that have not been benefited from AR systems among the selected studies: *Agriculture, forestry, fisheries and veterinary* and *Business, administration and law*.

Bacca et al. [9], conducted a literature review study in 2014, including 32 studies published between 2003 and 2013. While *Natural Sciences, Mathematics and Statistics* was the most explored broad field of education (40.6%), there were no applications related to the broad fields of *Agriculture, forestry, fisheries and veterinary*, or *Business, administration and law.*

Chen et al. [8], analyzed 55 studies published between 2011 and 2016, and found that, as well as in the study by Bacca et al., most AR applications were related to the Broad field of *Natural Sciences, Mathematics and Statistics* (40%). Likewise, they could not find any application related to the broad fields of *Agriculture, forestry, fisheries and veterinary*, or *Business, administration and law.*

In total, 127 AR systems from 2003 to 2017 (combining current study with the studies by Bacca et al. and Chen et al.) were analyzed and there was no evidence of applications related to the broad fields of *Agriculture, forestry, fisheries and veterinary*, and *Business, administration and law.*

Although AR systems have been proven to be more suitable to teach subjects such as Sciences and Engineering, there is a great opportunity for innovators to initiate the integration of AR into these unexplored broad fields of education. The importance of developing strategies for integrating AR systems into some unexplored fields of education is outlined below.

Agriculture and Forestry. Precision agriculture is a farming management concept, which integrates technology into agriculture with the intention of optimizing returns on inputs while preserving resources [22]. Issues such as climate change and a rapidly growing population around the world, brings new challenges to the farming processes. There is a clear need to develop more accurate farming methods, which provide opportunities for innovators to develop new technologies and techniques that help protect environment whilst increasing food production [23].

The most common technologies applied to precision agriculture are: precision positioning systems, automated steering systems, smart sensors, and integrated electronic communications. So far, AR systems have not been integrated into this vital field. This technology could be a useful and innovative tool that contributes to both precision agriculture and forestry. Hence, stakeholders have a great opportunity to begin exploring the possibilities that AR applications can provide to continue to enlarge the multiples benefits that technology can bring to agriculture development and forest conservation.

Business and Administration. Technology has important tangible and intangible effects on both business and administration. Technology plays an important role in some relevant aspects of business and administration, such as communication, efficiency of operations, information security, inventory management, business culture, and research capacity. Technology development has redefined business in ways that could not have been predicted. For example, the use of social networks has changed the way in which advertising is taken to customers. Internet, allows the exchange of information, databases, and possible money transferences, removing workplace boundaries, what enlarge the opportunities for expansion of enterprises and have increased the competitive nature of the business world [24].

Businesses have become so technology-dependent that if technology were taken away from companies, all business operations around the world would collapse. Having an efficient technology infrastructure allows administration systems to get more work done, faster, more efficiently, and more securely, which evidently improves business possibilities. In order to continue to expand business, and improve administration techniques, there is a need of continue to develop technological solutions. Hence, developers and practitioners can provide innovative and efficient AR systems that combined with business and administration theories can improve this type of processes.

4.3 Inclusion of AR Systems into Learning Processes of Unexplored Target Groups

Most common target groups for AR applications in the selected studies are *Secondary school* (35%), *Bacheloror equivalent level* (32.50%), and *Primary school* (25%). Oppositely, there are two target groups that have not been taken into account: *Post-secondary non-tertiary education* and *Short-cycle tertiary education*. These target groups corresponds to Vocational Education (VE), defined by the UNESCO as: "Education programmes that are designed for learners to acquire the knowledge, skills and competencies specific to a particular occupation, trade or class of occupations or trades" [25]. In VE, *Training*, is defined as "Education designed to achieve particular learning objectives".

The study by Bacca et al. [9], shows that only one study out of 32, focused on *Short-cycle tertiary education* astarget group. In addition, Chen et al., do not show any application that focuses on VE astarget group. In all, only one out of 127 AR applications, focused on Vocational Educations as target group (combining current study with the studies by Bacca et al. and Chen et al.).

Students in VE programmes, usually have completed secondary education, but due to different reasons, are not willing to enroll in a university. These students seek to prepare themselves to work in a trade, perhaps as a technician. This preparation includes training in manual or practical activities that are related to a specific occupation.

The inclusion of AR systems in training processes enriches the learning experience of students who can acquire knowledge on a more vivid way. However, the potential of this technology in VE has not been tapped, which means that innovators and stakeholders have a great opportunity to become leaders in this field.

4.4 Integration of AR Systems into Business and Industry

Although there is a notable reduction in the cost of AR systems, possibly due to the integration of this technology into mobile devices such as smartphones and tablets, a more significant participation of different economic sectors such as industry is needed. This with the intention of enlarging the investment for developing AR technologies, improve their affordances, and reduce final prices to the users.

A search for patents in two databases: the Global Patent Search Network (GPSN) of the United States Patent and Trademark Office (USPTO) [26] and Google Patents (GP), allowed us to identify that only a patent related to the AR technologies for education, has been registered in the last 10 years.

This apparent lack of interest in the industry for developing AR systems for education, may be due to entrepreneurs ignoring the good benefits that this emerging technology can bring to industrial processes. In addition, because researchers, developers and practitioners, have been unable to "sell the idea" to managers and policymakers within the industry.

With the purpose of integrating AR systems into industry, we propose two possibilities. The first has to do with the consideration of unexplored fields of application and the second has to do the consideration of unexplored target groups.

Unexplored Fields of Application. Companies related to agriculture are willing to invest money in new technologies that help improve farming processes [27]. The new technologies included in precision agriculture are drones, high precision position systems, smart sensors and aerial imagery. Data collected from these devices provides information to be used in machine learning and analytics software. The combination of these technologies with AR systems, could improve the monitoring, control, quality of predictive models in plant performance, and storage processes.

To make a difference in business, entrepreneurs have to be innovative, namely, to do things differently, cheaper, smarter, value added, or better quality. An important mechanism to be successful in business is to integrate new technologies into processes. Different studies have shown that organizations that have invested in technology (in the last two decades), have increased their market share, financial figures and overall competitiveness [28]. Augmented Reality holds the power to revolutionize the way we do business. It offers users graphical enhancements to the real environment that can be applied to marketing, sales, construction, communications and other forms of business that have not yet been deeply explored.

Unexplored Target Groups. The expansion of the global economy, has caused that labor market requires specific skills from workers, increasing the demand for vocational professionals. This have boosted the development of VE programs through publicly funded training organizations. However, the supply of these new required skills is not just responsibility of education or the government. Industry plays a central role in articulating the needed skills with the training curriculum [29].

Training processes in industry can be reinforced by the use of AR systems. This technology increases the depth of the instructions on even the more complex tasks. For example, AR overlaying make possible the illustration of step-by-step reparation processes of any machinery for inexperienced workers. Hence the integration of AR systems into business and industry, can be achieved by the inclusion of AR applications that are designed to support training processes for VE programs students.

4.5 Design of Pedagogically Efficient AR Systems

Sometimes, AR applications are evaluated only taking into account their technical efficacy. These applications are designed by professional programmers and consequently their quality in terms of technology is out of discussion [30]. Technical or technological issues reported in the studies have decreased in the last years. Most of the problems that used to present AR applications have been solved. This has to do probably with the fact that these applications have been widely integrated into mobile devices such as smartphones and tablets [31], which are mature technologies. However, these applications have to go beyond technical characteristics. What is important here, is not only that these systems work properly, but that satisfy the real purposes of education.

Engineers have abilities for technical issues such as designing, programming, assembling, among others. Nevertheless, these abilities are not sufficient when the purposes have to do with pedagogical issues. On the other hand, thematic and pedagogical experts such as teachers, may not have the capacity to develop these tools because they lack the programming and assembling skills.

So, how to design AR applications that are technically efficient and pedagogically accurate? As stated by Diegmann et al., AR applications are not magical bullets in educational environments. Every application is unique and has to be designed to be applied in a specific scenario [6]. We have to remember that as well as other technological applications, AR systems are merely pedagogical tools that have to be complemented by an appropriate pedagogical content, and their design and usage have to be guided by a thematic expert. Namely, the tool does not replace the teacher, it just complements the learning process.

Teachers and stakeholders with no programming experience, may use "Authoring Tools" to create their own AR applications. These intuitive interfaces permit the user to create learning environments without the necessity of using programming languages. Some of the most popular Authoring tools that can be accessed to create AR applications are ATOMIC, AMIRE, and ComposAR.

However, in order to ensure the quality of any Digital Educational Resource (DER), its development should involve the participation of an interdisciplinary group of professionals, each one of whom is responsible for developing a specific activity under the guidelines of an Instructional Design Model. Instructional Design models involve activities that are systematically related and seek to maximize the process of educational software development [32].

There are many Instructional Design models, which are composed mostly of five basic phases: Analysis, Design, Development, Implementation, and Evaluation. Due to its simplicity, versatility, linearity and other benefits, in this paper we recommend the Instructional Design Model "ADDIE" [33]. Figure 1 represents the interaction of each phase in the Instructional Design Model ADDIE.

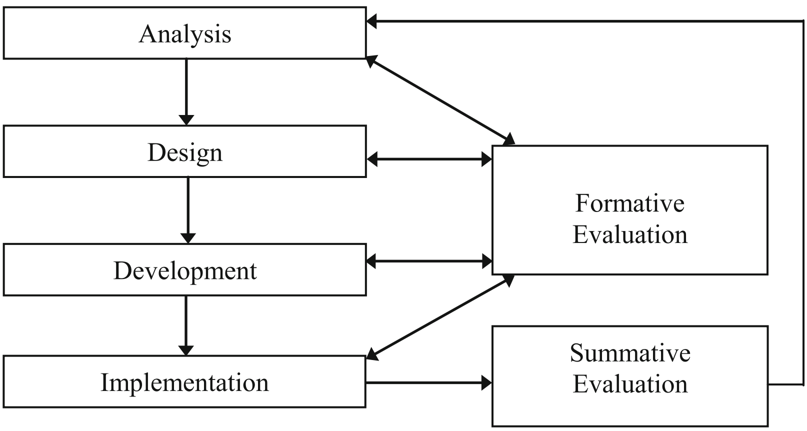

Fig. 1. Instructional design model

Analysis. The analysis phase is the basis for the remaining phases of the instructional design. In this phase, it is necessary to define the nature of the problem, identify its origin and propose some possible solutions. This phase may include specific research techniques such as user analysis, pedagogical context analysis, and analysis of specific needs. Some usual results of this stage are the Educational goals and a list of activities to be developed. These results are the inputs to the Design phase.

Design. This phase uses the results of the Analysis phase, to plan a strategy for developing the instruction. In this phase, it is necessary to establish some routes to reach the Educational Goals. Some elements of the Design phase include the objectives of the DER, the thematic contents, and the assessment instruments.

Development. This phase is based on the phases of Analysis and Design. Its purpose is to generate the structure of the instruction. All the pedagogical materials such as thematic content, activities, and assessment instruments are created. In this phase, programmers develop or integrate technologies.

Implementation. This phase refers to the delivery of the instruction. This is the start of the learning process, all the materials created in the Development phase are introduced to the target learners. It focuses on developing training for both educators and learners. This phase may include re-design work in order to correct found issues.

Evaluation. This phase measures the effectiveness of the instruction. The evaluation can be formative, within each phase of the process, or summative, at the end of the implementation of the instruction.

5 Conclusion

In this paper, we propose five directions for future research around practical solutions for some of the challenges of AR systems for education. We analyzed, classified and synthetized the challenges reported in 50 scientific papers that included case studies and literature review studies. The proposed directions have to do with the need of addressing special requirements of users, the opportunities for developing unexplored broad fields of education and unexplored target groups, and possible strategies to integrate AR into industry, looking to obtain funding for the development of this emerging technology. Despite its proven efficacy when applied in educational settings, AR systems still have some problems to overcome. In order to continue improving the possibilities and trying to extend its benefits to each educational scenario, stakeholders and practitioners must continue to address all gaps and develop strategies to solve challenges encountered.

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9.Meta-analysis of the impact of Augmented Reality on students' learning gains

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Summary:

Our second specific objective proposes to identify the impact of AR applications on education. To our knowledge, four meta-analyses of AR on education were published before this doctoral thesis. However, the previous meta-analyses present three major limitations: First, they do not standardize the results of studies with different research designs, which yields a small number of meta-analyzed studies. Second, meta-analyses with small samples suffer from publication bias. Third, such a small sample avoids them to accurately perform moderator analyses.

In an attempt to bridge those research gaps, we conducted a meta-analysis of 64 empirical studies published in scientific journals. The purpose of the meta-analysis was to identify how AR systems influence the learning outcomes of students in order to guide future development of AR applications for education. In addition, the study identified to what extent population characteristics (level of education), intervention characteristics (learning environment, display device), and context characteristics (field of education) moderate students' cognitive outcomes.

As a result, the study identified that AR has a medium effect on the learning gains of students. The study also compared AR applications with other types of pedagogical resources including multimedia resources, traditional lectures, and traditional pedagogical tools. The results indicated that the learning gains are higher when the intervention involves AR resources. Furthermore, the study identified that *Bachelor level* students and *Primary education* students seem to benefit the most from AR. Likewise, AR systems show a higher impact when used to teach subjects related to the broad fields of *Engineering* and *Arts and Humanities*. Finally, the study discusses the implications of the results for theory and practice and establishes some possible routes of investigation for future work.

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Review

Meta-analysis of the impact of Augmented Reality on students' learning gains

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ABSTRACT

Existing literature reflects the multiple benefits of the integration of Augmented Reality (AR) technologies in educational settings. Many studies have been conducted to establish the tendencies, affordances, and challenges of this technology for education. However, most of these studies are qualitative studies that do not measure the extent of the impact of this technology on education. This study conducted a meta-analysis of 64 quantitative research papers (N = 4705) published between 2010 and 2018 in major journals. The main purpose of the study was to analyze the impact of AR on students' learning gains. Furthermore, the study analyzed the influence of moderating variables such as control treatment, learning environment, learner type, and domain subject on the learning gains. The results identified that AR has a medium effect on the learning gains of students ($d = .68$, $p < .001$). Additionally, the study discusses the effect of AR on the moderating variables and establishes some possible routes of investigation for future work.

1. Introduction

Augmented Reality (AR) is an important technology that provides significant tools to improve the experience of interacting with reality. The term "Augmented Reality" was coined by Caudell and Mizell (1992) to describe the technology that enables users to augment the visual field by using heads-up display technology. Azuma (1997) defined AR as the technology that allows users to see a supplemented reality through superimposed virtual objects over the real world. However, this definition needed to be broadened considering that AR can be applied to all senses and not only to the sense of sight. In this way, Akçayir and Akçayir (2017) proposed a simple, accurate, and wide definition of AR as the technology that overlays virtual objects in the real world.

The rise of personal mobile devices, especially since 2010 (Mekni & Lemieux, 2014), has led to an accelerated growth of AR applications in many areas such as tourism, medicine, industry, and education. The inclusion of AR systems in each of these areas has been proven to be positive (Billinghurst, Clark, & Lee, 2015; Martin et al., 2011; Mekni & Lemieux, 2014; Yim, Chu, & Sauer, 2017) and consequently, developers and practitioners have continued to develop and improve AR applications to be integrated into our daily lives.

1.1. Augmented Reality in education

2017; Antonioli, Blake, & Sparks, 2014; Diegmann, Schmidt-Kraepelin, Eynden, & Basten, 2015). These studies have shown that AR applications for education are steadily increasing since 2010 and have effectively taken root in educational settings (Garzón,

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Pavón, & Baldiris, 2019; Ozdemir, Sahin, Arcagok, & Demir, 2018; Radu, 2014; Santos et al., 2014). Bacca, Fabregat, Baldiris, Graf, and Kinshuk (2014) conducted a systematic literature review that included 32 papers from 2003 to 2013. The study found that AR is most applied to teach Natural Sciences and Mathematics and that the most common target group of AR applications is bachelor students. It also revealed that the most reported advantages of AR in education are learning gains and motivation. On the other hand, maintaining superimposed information and the consideration of AR as an intrusive technology are some of the main limitations of AR systems. Similar findings have been reported by other studies (FitzGerald et al., 2013; Tekedere & Göker, 2016; Z. A.; Yilmaz & Batdi, 2016) establishing a complete description of the benefits and challenges of AR for education.

However, most of the existing literature corresponds to the narrative-based and qualitative literature reviews. That is, those studies describe through narrative the findings on qualitative variables and do not consider quantitative variables to measure the impact of this technology on education.

1.2. Meta-analysis

As an alternative to qualitative methods, some leading journals and researchers have encouraged the use of meta-analyses, one of the most common quantitative methods in the social and behavioral sciences (Hedges & Olkin, 1985). It was defined as “the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating findings” (Glass, 1976, p. 3). Meta-analyses proceed from particular observations to general statements. The particular observations are found in the effect size (ES) that represents the magnitude of experimental effect transformed to a standardized mean difference. Meta-analyses combine relative samples and ES's from different studies. Therefore, the overall result is more precise because of the magnitude of the analysis, which allows establishing general statements. In addition, the fact that meta-analyses focus on comparison studies versus one-shot studies allows control of internal validity (Bernard et al., 2004). In summary, meta-analyses are more objective and less judgmental than literature reviews. However, meta-analyses present some important limitations such as publication bias and sampling bias, which must be considered when reporting meta-analysis results (Cohen, 1992b).

1.3. Previous meta-analyses on the impact of AR on education

To our knowledge, five meta-analyses that measure the impact of AR on education have been published in major journals. Santos et al. (2014) meta-analyzed seven studies to evaluate the ES of AR on education. They concluded that AR has a moderate effect on student performance according to the mean ES found of 0.56. Tekedere and Göker (2016) conducted a meta-analysis to examine the methods of the studies on the use of AR in education and calculate the influence quantity. The research included 15 quantitative studies and the average ES found was 0.67. The main conclusion of the study was that AR has a positive effect on students. In the same way, Yilmaz and Batdi (2016) evaluated the efficacy of AR applications in the learning environment. They analyzed 12 studies and found a mean ES of 0.36, which corresponds to a small effect. Ozdemir et al. (2018) investigated the effect of AR applications in the learning process. The research included 16 studies and the average ES found was 0.51. Finally, Garzón et al. (2019) conducted a literature review and meta-analysis of 27 studies to identify the status, tendencies, opportunities, and challenges of AR in education. Their study found that AR has an ES of 0.64 on learning effectiveness and concluded that AR is reaching maturity in educational settings. With the exception of the study by Yilmaz and Batdi (2016), all these meta-analyses present the same conclusion “AR applications have a positive impact on education”. However, the aforementioned meta-analyses present three important limitations. First, they do not standardize the findings of studies with different research designs for direct comparison, which yields a small number of meta-analyzed studies (Carlson & Schmidt, 1999). Second, meta-analyses with small samples are more likely to suffer from random noise and publication bias (Gurevitch, Koricheva, Nakagawa, & Stewart, 2018). Third, such a small sample in these meta-analyses does not allow them to accurately perform moderator analyses to assess the variables that may influence the impact of AR on education.

1.4. Purpose of the study

This meta-analysis takes a step further by integrating findings across studies with different research designs. Additionally, a moderator analysis involving control treatment, learning environment, level of education, and field of education, was performed to investigate conditions under which AR may have different effects on learning outcomes of students. These variables have been identified as moderators in previous studies (Akçayir & Akçayir, 2017; Baldiris, Fabregat, Bacca, Avila, & Zervas, 2014; Chauhan, 2016; Garzón et al., 2019; Mekni & Lemieux, 2014; Ozdemir et al., 2018; Santos et al., 2014) and represent the basis for our moderator analysis. In this study, ES is understood as a quantitative reflection of the magnitude of AR's impact on education (Kelley & Preacher, 2012) and “impact” refers to students' learning outcomes.

With the previous background, this meta-analysis proposes to 1) recover, synthesize, and integrate the existing literature measuring the impact of Augmented Reality on students' learning gains, 2) identify how some moderator variables influence the impact of Augmented Reality on students’ learning outcomes.

The purpose of this meta-analysis is to identify how AR systems influence the learning outcomes of students in order to guide future development of AR applications for education. To achieve this purpose, we identify to what extent population characteristics (level of education), intervention characteristics (learning environment), and context characteristics (field of education) moderate students’ cognitive outcomes.

We followed the PICO framework to formulate the research questions (Higgins & Green, 2011). The elements of the PICO framework are *Population*, *Intervention*, *Comparison*, and *Outcomes*. In this study, the *Population* is composed of students enrolled in educational institutions (from early childhood education to doctoral programs). The *Intervention* considered is the use of AR applications in educational environments. The *Comparison* is made with traditional teaching methods (lectures), traditional pedagogical tools, and other educational resources based on technology (multimedia resources). Finally, the *Outcomes* of the application of these methods are measured in terms of student's learning performance. As a result, we elaborated five research questions (RQ) that guide the purpose of the study:

RQ1: What is the effect of AR on students' learning gains?
RQ2: Are the learning gains higher when using AR applications as compared to other educational resources?
RQ3: How does the effect of AR vary according to the learning environment?
RQ4: What is the impact of AR applications according to the level of education?
RQ5: What is the impact of AR applications according to the field of education?

In this study, learning gains (RQ1) is defined as the improvement of students' learning outcomes between the beginning and the end of the intervention through AR applications. Educational resources (RQ2) refer to pedagogical tools and methodologies that provide support to complement learning and teaching processes (Multimedia, Traditional Lectures, and Traditional Pedagogical Tools). Learning environment (RQ3) refers to the context in which interventions are carried out (formal, informal, and unrestricted settings). To organize the studies per level of education (RQ4), we used the classification proposed by the International Standard Classification of Education ISCED (UNESCO, 2011). Finally, regarding the field of education (RQ5), we used the broad fields of education proposed by the International Standard Classification of Education ISCED (UNESCO, 2011).

1.5. Moderator variables

Moderator variables refer to characteristics of studies that are correlated with studies' results. The search for moderators involves the verification that results are different for different subgroups of studies. The most common moderator variables in previous studies are control treatment, learning environment, learner type (level of education), and domain subject (field of education). Therefore, and also as a result of following the PICO framework, we considered these variables as a starting point. Next, we describe the moderator variables that were considered for the moderator analysis:

A. Control treatment: it refers to the pedagogical strategy that was implemented in the control groups. The analysis of this moderator is important to identify the learning that can be attributed specifically to AR as recommended by Santos et al. (2014). Previous meta-analyses related to other technologies, have considered "control treatment" as a moderating variable to compare the experimental treatment against different control group treatments (Lee, 1999; Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014; Sitzmann, 2011). We classified the control treatments into three pedagogical strategies: 1) *Multimedia* that refers to educational resources that uses different content forms such as videos, images, animation, and learning objects, 2) *Traditional Lectures* that refers to curriculum-based and lecture-based teaching, and 3) *Traditional Pedagogical Tools* that refers to traditional educational resources that teachers use to complement their lectures.
B. Learning environment: it refers to the environment where the intervention was carried out. We considered the three types of environments proposed by Chauhan (2016) in her qualitative study: 1) formal settings (classroom, laboratory), 2) informal settings (home, field trips, museums, outdoor activities), and 3) unrestricted settings (including both formal and informal settings). Providing information on the impact of AR according to the learning environment, turns out to be very important for developers and teachers. It is important to identify which contexts favor learning when using AR applications, so that students can make the most of the advantages of using this technology. This variable has been analyzed by different qualitative studies (Akçayir & Akçayir, 2017; Antonioli et al., 2014; Wu, Lee, Chang, & Liang, 2013); however, our meta-analysis provides quantitative data that are expected to guide accurately future decisions of stakeholders.
C. Level of education: it refers to the target groups that participated in each study. We divided this category into 9 sub-categories according to the International Standard Classification of Education (UNESCO, 2011). The analysis of the effects of AR applications according the level of education has been of great interest to the research community. This variable has been included for analysis in a significant number of qualitative studies (Akçayir & Akçayir, 2017; Bacca et al., 2014; Bower, Howe, McCredie, Robinson, & Grover, 2014; Garzón et al., 2019; Ozdemir et al., 2018). However, these studies are limited to establishing at what levels AR is most used, and do not provide quantitative information about the extent of the impact of this technology on students' learning gains. One of the purposes of this study is to guide future development of AR applications for education. Accordingly, identifying the levels of education that seem to benefit most from AR can be of vital importance for developers and practitioners.
D. Field of education: it refers to the domain subject of the AR application in each study. We divided this category into 10 sub-categories according to the broad fields of education proposed by the International Standard Classification of Education (UNESCO, 2011). Previous qualitative studies (Akçayir & Akçayir, 2017; Bacca et al., 2014; Garzón et al., 2019; Ozdemir et al., 2018; Tekedere & Göker, 2016) have analyzed the domain subject of AR applications. These studies have identified the most common fields of education for AR applications and have indicated what levels should be further explored. With our work, we hope to guide future developments by providing information on the extent of the impact of AR in each of these fields.

2. Method

This study followed a rigorous research process in order to collect, assess, and summarize empirical evidence related to the research questions. Sixty-four quantitative studies from major journals that measured the impact of AR on students' learning outcomes were selected for the analysis. This meta-analysis was conducted in accordance with the PRISMA guidelines (Moher, Liberati, Tetzlaff, & Altman, 2009) and follows recommendations outlined by Glass, Smith, and McGaw (1981). This procedure requires a meta-analysist to a) collect studies, b) code study features, c) calculate ES's of each study on a common scale, and d) investigate moderating effects of study's characteristics. Below, we provide detailed information on these activities.

2.1. Selection of the studies

To identify the primary studies to answer the research questions, we looked for scientific papers in the three major bibliometric databases: Web of Science, Scopus, and Google Scholar (Harzing & Alakangas, 2016). We searched the following keywords: *Augmented Reality*, *Augmenting Reality*, and *Mixed Reality* combined with *Education, Learning*, *Training*, *Teaching*, and *Instruction*. The final search was conducted on January 4, 2019, and allowed us to find 527 studies. We did not include unpublished studies, because the evaluation of their quality cannot be guaranteed in the absence of a peer review process.

Each paper was screened by the two researchers to identify its suitability for the study. The papers that did not accomplish the eligibility criteria were discarded. Missing information in the studies was requested via email to the corresponding authors. If the information was not received in the following month, the study was also discarded.

2.1.1. Eligibility criteria

Studies were primarily selected based on their title and keywords. The title and keywords of all the extracted studies were manually scanned to eliminate apparently irrelevant studies. This process resulted in 314 studies. Next, we read the abstract of each study. This allowed us to eliminate documents other than papers, review papers, non-English papers, qualitative papers and papers that did not address the purpose of the study. This process resulted in 118 papers. Next, we selected studies that fulfilled the following conditions: a) empirical studies that measured the impact of AR on students' learning gains as an outcome variable, b) studies that provided sufficient information for calculating the ES (standard deviations, mean scores, and sample sizes), and c) studies that included a control condition (pretest – posttest or control group – experimental group).

These criteria led to a selection of 64 academic papers. Next, we scanned the reference list of each paper, but it did not result in the identification of any new relevant study. As usual in literature reviews, Cohen's kappa was used to verify the inter-coder reliability in each exclusion level (Cohen, 1968). Thus, 64 studies published between 2010 and 2018 (see Fig. 1) were identified as relevant to the purpose of this study. It is worth mentioning, that our sample includes the studies meta-analyzed in the previous meta-analyses on the impact of AR on education.

2.2. Data coding

We designed a data extraction form to collect the information to address the research questions. Each paper was read by the two researchers, who used the content analysis technique as recommended by Hsu, Hung, and Ching (2013) to extract the data. The data form included the following information: title, authors, year of publication, sample size, type of research design, control treatment, learning environment, learner type, domain subject, intervention duration, mean values and standard deviations for pretest and posttests for both experimental and control groups (according to the research design), and an additional space for observations.

Cohen's kappa statistic was used to measure inter-coder reliability. This value was found to be 0.95 that corresponds to "almost perfect agreement" as stated by Cohen (1968). Occasional disagreements were discussed and resolved by consensus.

2.3. Calculation of the ES

The objective of the meta-analysis is to synthesize the quantitative information collected from the studies. The meta-analysis is used to estimate the ES of AR on students' learning gains; these gains were assessed based on Cohen's d ES.

We followed the guide proposed by Morris and DeShon (2002) for calculating d values from different research designs. One of the challenges of performing the meta-analysis is to deal with data from different research designs. The evaluation of interventions differs among studies in the use of control and experimental groups or in the application of pretests and posttests. This meta-analysis integrates the results of three different research designs. First, the Pretest-Posttest-Control (PPC) design in which participants are assigned to experimental or control groups, and each participant is evaluated before and after the treatment. Second, the Posttest Only with Control (POWC) design in which participants are assigned to experimental or control groups, but does not include a pretest. Third, the Single-Group Pretest-Posttest (SGPP) design that does not include a control group, but evaluates participants before and after the treatment.

The PPC design affords more accurate estimates of d and provides greater control over threats to internal validity (Morris, 2008). Notwithstanding, our meta-analysis seeks to integrate findings across different research design studies, to accumulate a larger sample and mitigate random noise existing in meta-analyses with small samples. Thus, the variation in the research design between the studies led us to consider also POWC and SGPP designs that generate similar values. Table 1 shows the distribution of the studies according to their research design.

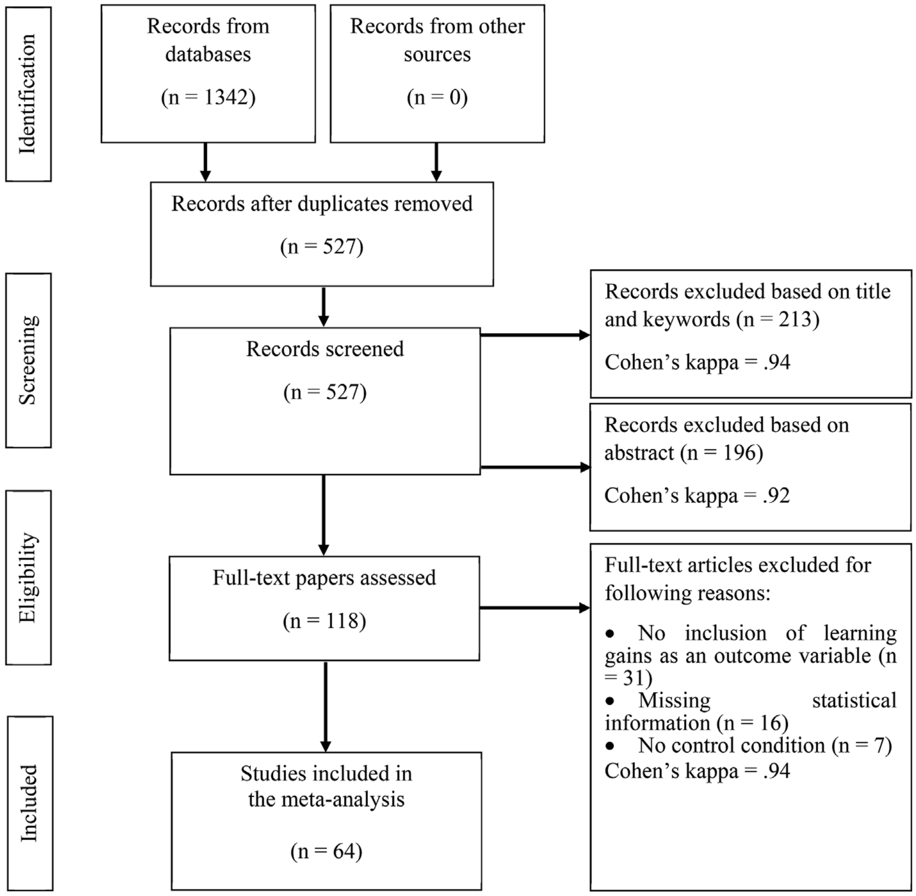

Fig. 1. PRISMA Flowchart for the studies selection process.

Table 1
Distribution of the studies per research design.

Research design	Number of studies
PPC	40
POWC	8
SGPP	16
Total	64

Nevertheless, ES's from different research designs cannot be directly compared as they estimate different population parameters (Ray & Shadish, 1998). Morris and DeShon (2002) pointed out that ES's from different research designs can be combined only if the following three requirements are met. First, ES's from each design estimate the same treatment effect. Second, all ES's can be transformed into a common metric (raw-score metric or change-score metric). Third, meta-analysis procedures use design-specific estimates of sampling variance to reflect the precision of the ES's estimate.

To answer RQ1, we selected student's learning outcomes as the dependent variable in all the studies. As described by Hedges (1982) we used a two-step procedure: first we calculated the ES of each study, and second, we transformed each ES into a common metric. When a study provided several mean scores and standard deviations, they were averaged and the average was used to calculate the ES (Bernard et al., 2004). To estimate the ES from PPC design studies (d_{PPC}), we computed a separate ES within the control and experimental groups. Then, we used the difference between the two values to estimate the overall ES for the study (Becker, 1988):

$$d_{PPC} = \frac{(M_{E\_Post} - M_{E\_Pre})}{SD_{E\_Pre}} - \frac{(M_{C\_Post} - M_{C\_Pre})}{SD_{C\_Pre}}$$

where M_{E_Post} and M_{E_Pre} are the mean scores of posttest and pretest for experimental group respectively, and M_{C_Post} and M_{C_Pre} are the mean scores of posttest and pretest for control group respectively. Likewise, SD_{E_Pre} and SD_{C_Pre} are the standard deviations of the experimental and control groups respectively for the pretest.

To identify the ES for POWC design studies (d_{POWC}), we used Hedges (1982) definition as follows:

$$d_{POWC} = \frac{M_{POST\_E} - M_{POST\_C}}{SD_{POST}}$$

where M_{POST_E} and M_{POST_C} are the mean scores of experimental and control groups respectively, and SD_{POST} is the pooled within-group standard deviation of the posttest scores:

$$SD_{POST} = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{(n_1 + n_2 - 2)}}$$

To identify the ES for SGPP (d_{SGPP}) design studies, we used the definition proposed by Gibbons, Hedeker, and Davis (1993) for repeated measures design as follows:

$$d_{SGPP} = \frac{M_{POST\_E} - M_{PRE\_E}}{SD_{D\_E}}$$

where M_{POST_E} and M_{PRE_E} are the mean scores of pretest and posttest, respectively and SD_{D_E} is the sample standard deviation of change scores.

Two SGPP design studies (Cai, Wang, & Chiang, 2014; Chang, Wu, & Hsu, 2013) did not provide mean scores and standard deviations. Instead, they provided t-test values. To transform t-test values into d_{SGPP}, we used the following formula provided by Rosenthal (1991):

$$d_{SGPP} = \frac{t_{SGPP}}{\sqrt{n}}$$

where, n is the number of students in the case study.

The guidelines for interpreting ES's values were $d = .2$ (small effect), $d = .5$ (medium effect), $d = .8$ (large effect) (Cohen, 1992a), $d = 1.2$ (very large effect), and $d = 2.0$ (Huge effect) (Sawilowsky, 2009).

2.4. Combination of ES's from different research designs

Combining ES's from different research designs requires that all ES's be in the same metric (Glass et al., 1981), either in the raw-score metric (PPC, POWC) or in the change-score metric (SGPP). Given the fact that ES's from different research design estimate different population parameters, all ES's must be transformed into a common metric. Hence, the meta-analyst must decide which metric will be used according to the purpose of the analysis (Morris & DeShon, 2002).

When the purpose of the meta-analysis is to find differences within an individual before and after treatment, the change-score (repeated measures design) is a suitable metric. In this research design, all individuals are exposed to the same treatment and change in performance within individuals is attributed to the intervention. However, this change can also be attributable to other external variables such as retesting, maturation, and regression to the mean. This makes the interpretation of the results ambiguous, which represents the main drawback of using this metric. Alternatively, when the purpose of a meta-analysis is to find differences between alternate treatments, the raw-score (independent groups design) is a suitable metric. In these research designs, every individual is subjected to a single treatment (experimental or control) and each participant is evaluated only once (POWC) or before and after the intervention (PPC). These research designs compare the extent of change attributable to the treatment to the change in a control group. The results of the control group provide information about the change attributable to the external variables (retesting, maturation, and regression to the mean) and the pretest scores provide information about the prior knowledge of the participants (in PPC design). The purpose of this study is to identify how AR systems influence the learning outcomes of students and, therefore, we selected the raw-score as the common metric for the meta-analysis.

To transform a repeated-measures ES (change-score metric) into independent-groups ES (raw-score metric) we used the following formula that has been broadly used in different studies (Becker, 1988; Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Cortina & Nouri, 2000; Dunlap, Cortina, Vaslow, & Burke, 1996; Gibbons et al., 1993; Morris & DeShon, 2002):

$$d_{IG} = d_{RM}\sqrt{2(1 - \rho)}$$

where, d_{IG} is the transformed ES for the raw-score metric, d_{RM} is the ES for the change-score metric, and ρ is the correlation between scores.

In order to combine PPC ES's with POWC ES's, meta-analysts must assume that experimental conditions had similar variance (Becker, 1988; Cepeda et al., 2006; Cohen, 1988; Morris, 2008). An expected source of unequal variance is the data that show ceiling or floor effects. Variances at different research design in our data do not show variations by more than five percent according to Levene's test ($F = 2.24$, $p = .14$). Therefore, we assumed that the variance of the scores is homogeneous across time.

2.5. Moderator analysis

We used the homogeneity analysis of Hedges and Olkin (1985) to identify if the ES's were homogeneous across studies. For main effect analysis, the set of ES's was evaluated for homogeneity with the Q, I^2, and p statistics (see Table 3). The analysis of the values of

Table 2
Summary of the studies of the meta-analysis sorted by publication date.

Author	d_{IG}	V_{IG}	W_{IG-R}	$W_{IG-R} * d_{IG}$
Martín-Gutiérrez et al. (2010)	.65	.09	8.34	5.42
Liu and Chu (2010)	.78	.06	11.28	8.80
Chen, Chi, Hung, and Kang (2011)	.91	.17	5.01	4.56
Chen and Tsai (2012)	.27	.04	15.43	4.18
Hsiao, Chen, and Huang (2012)	.92	.01	24.74	22.69
Enyedy, Danish, Delacruz, and Kumar (2012)	1.66	.03	16.80	27.97
Di Serio, Ibáñez, and Kloos (2013)	.67	.02	21.17	14.26
Lin, Duh, Li, Wang, and Tsai (2013)	.85	.03	16.12	13.71
Cai, Chiang, and Wang (2013)	-.02	.07	10.11	-.20
Kamarainen et al. (2013)	.48	.02	21.42	10.27
Chang et al. (2013)	.58	.06	10.77	6.30
Hsiao (2013)	1.44	.06	11.01	15.81
Chang et al. (2014)	1.00	.04	13.94	13.94
Zhang, Sung, Hou, and Chang (2014)	.43	.05	12.22	5.25
Cai et al. (2014)	.68	.05	13.16	8.98
Sommerauer and Müller (2014)	1.03	.05	12.07	12.43
Ibáñez, Di Serio, Villarán, and Delgado Kloos (2014)	.97	.06	11.79	11.44
Gutiérrez and Meneses Fernández (2014)	.79	.08	9.46	7.47
Jee, Lim, Youn, and Lee (2014)	.37	.03	17.31	6.34
Lu and Liu (2015)	2.82	.13	6.46	18.22
Lin, Chen, and Chang (2015)	.16	.04	14.89	2.38
Schmitz, Klemke, Walhout, and Specht (2015)	.32	.08	9.12	2.92
Ferrer-Torregrosa, Torralba, Jimenez, García, and Barcia (2015)	.67	.02	23.07	15.46
Fonseca, Redondo, Villagrasa, and Canaleta (2015)	2.23	.04	23.07	32.58
Ke and Hsu (2015)	.79	.04	14.61	11.57
Cheng, Lin, and She (2015)	.36	.02	20.20	7.24
Chiu, DeJaegher, and Chao (2015)	.40	.03	17.22	6.87
Chen et al. (2015)	1.21	.01	27.01	32.55
Chang, Hou, Pan, Sung, and Chang (2015)	1.71	.17	4.98	8.51
Barma, Daniel, Bacon, Gingras, and Fortin (2015)	.45	.05	13.33	6.00
Wang, Wu, Chien, Hwang, and Hsu (2015)	.57	.02	20.05	11.52
Tarng, Ou, Yu, Liou, and Liou (2015)	.89	.13	6.38	5.68
Ibanez, Di Serio, Villaran, and Delgado Kloos (2016)	.32	.04	14.81	4.74
Huang, Chen, and Chou (2016)	1.01	.24	3.77	3.82
Chen, Lee, and Lin (2016)	1.78	.34	2.72	4.83
Chen, Chou, and Huang (2016)	-.05	.07	10.62	-.53
Akçayir, Akçayir, Pektaş, and Ocak (2016)	.64	.10	7.77	4.97
Küçük, Kapakin, and Göktaş (2016)	.67	.05	13.07	8.80
Juan, Alexandrescu, Folguera, and García-García (2016)	-.23	.13	6.42	−1.48
Tarng, Lin, Lin, and Ou (2016)	.51	.06	11.71	5.97
Cai, Chiang, Sun, Lin, and Lee (2017)	.54	.25	3.64	1.97
Safar (2017)	2.90	.37	2.54	7.36
Hsu (2017)	.75	.10	8.12	6.08
Mumtaz et al. (2017)	.39	.13	6.45	2.52
Joo-Nagata, Martinez Abad, García-Bermejo Giner, and García-Peñalvo (2017)	.91	.09	8.42	7.66
Wang (2017)	.39	.03	17.68	6.82
(Yi Hsuan Wang, 2017)	.84	.14	5.94	4.99
(Tosik Gün & Atasoy, 2017)	.19	.04	15.10	2.87
Calle-Bustos, Juan, García-García, and Abad (2017)	.62	.08	8.87	5.50
Tobar-Muñoz, Baldiris, and Fabregat (2017)	.38	.08	9.07	3.45
Yilmaz and Goktas (2017)	.99	.04	14.81	14.67
Widiaty, Riza, Danuwijaya, Hurriyati, and Mubaroq (2017)	.61	.05	12.85	7.75
Hwang and Chen (2017)	.44	.03	17.67	7.73
Liou, Yang, Chen, and Tarng (2017)	.90	1.36	.72	.65
Cascales-Martínez, Martínez-Segura, Pérez-López, and Contero (2017)	.27	.06	10.77	2.92
Aebersold et al. (2018)	.64	.05	13.77	8.43
Karagozlu (2018)	4.25	.28	8.67	36.85
Wang, Huang, Liao, and Piao (2018)	.80	.18	4.84	3.88
Tarng, Ou, Lu, Shih, and Liou (2018)	.91	.54	1.77	1.61
Turan, Meral, and Sahin (2018)	1.03	.04	14.02	14.44
Chang and Hwang (2018)	.26	.02	19.39	5.04
Medina, García, and Olguín (2018)	.80	.22	3.39	3.19
Wu, Hwang, Yang, and Chen (2018)	.94	.08	9.35	8.79
Chao and Chang (2018)	.43	.04	14.03	6.03

Note. d_{IG} is the transformed ES estimate; V_{IG} is the estimated sampling variance of the ES's, and W_{IG-R} is the value used to weight the ES estimates. There was one unusually huge ES of $d = 4.25$ (Karagozlu, 2018). Studies with d values greater than the mean d value of the entire sample by more than three standard deviations are likely to bias the overall ES calculation. Therefore, this study was excluded from the analysis as recommended by Lipsey and Wilson (2001).

Table 3
Summary of the meta-analysis results.

Variable	Overall
Number of samples (*K*)	64
Total sample size (*N*)	4705
Effect Size (*d*)	.68
Standard score *(Z)*	19.86
Probability value *(p)*	< .001
Heterogeneity test (*Q*)	252.27
Heterogeneity test (I^2)	76.22
95% Lower limit	.61
95% Higher limit	.75

these statistics led us to reject the null hypothesis of homogeneity, which suggests that it is appropriate to test for moderators.

The purpose of the moderator analysis was to identify whether the effectiveness of AR on students' learning, differed based on specific characteristics of each study such as the control treatment, the learning environment, the level of education, or the field of education. As recommended by Lipsey and Wilson (2001), we tested the moderating effects by classifying the studies according to the moderator categories, and then, testing for homogeneity between and within categories.

3. Results

The combined effect of the 64 studies was calculated using the random-effects model. The motivation for this assumption was that the samples in individual studies were taken from populations that had varying ES's (Hedges, 1982). Table 2 presents the studies of the meta-analysis and summarizes the calculated values.

3.1. RQ1: what is the effect of AR on students' learning gains?

To compute the overall ES of AR on students' learning gains, we took the sum of the weighted ES's ($W_{IG-R} * d_{IG}$) and divided it by the sum of the representing random-effects weights (W_{IG-R}) (Card, 2011). This equation yielded an overall $d = .68$ that corresponds to a medium effect (Cohen, 1992a). Table 3 summarizes the ES path coefficients for all the studies.

Heterogeneity of the studies was tested according to the *Q*, I^2, and *p* values. *Q* statistics tend to highlight even small heterogeneity when the meta-analysis is performed on a large number of studies (Huedo-Medina, Sánchez-Meca, Marín-Martínez, & Botella, 2006). The *Q* value was found to be higher than the critical value ($Q = 252.27 > 81.38$), for the 63 degrees of freedom at 95% significance level from the Chi-square distribution table. This indicated the rejection of the null hypothesis of homogeneity and led us to accept the alternate hypothesis of heterogeneity. Likewise, I^2 index measures the degree of true heterogeneity (Higgins & Thompson, 2002). The found I^2 index value indicates a large amount of heterogeneity as suggested by Huedo-Medina et al. (2006). Finally, a *p* value lower than 0.05 as depicted in Table 3, also indicates heterogeneity. These three values support our assumption of the random-effects model.

3.2. RQ2: are the learning gains higher when using AR applications as compared to other educational resources?

The *d* value shown in Table 3 indicates that AR has a medium effect on education. However, it is necessary to verify that this effect is the reflection of AR per se. That is, it is important to identify that this effect is not the result of any intervention, but the result of the intervention with AR technologies. To identify this, we compared the effects of the AR treatments against the treatments applied in the control groups (see Table 4). Considering that SGPP research designs do not include a control group, the comparison included only POWC and PPC research designs. We classified the control treatments into three pedagogical strategies:

A. Multimedia: it refers to educational resources that uses different content forms such as video assisting teaching, images,

Table 4
Comparison of AR applications with other pedagogical strategies.

Variable	Multimedia	Traditional Lectures	Traditional Pedagogical Tools
K	18	17	13
N	1751	1277	916
d	.67	.61	.61
Z	17.89	14.86	9.70
p	< .001	< .001	< .001
Q	252.27	277.19	451.97
I^2	93.26	94.59	97.34
95% Lower limit	.59	.53	.49
95% Higher limit	.74	.69	.73

Table 5
Summary of moderator analysis per learning environment.

Variable	Formal settings	Informal settings	Unrestricted settings
K	47	15	2
N	3475	1134	121
d	.67	.80	.68
Z	18.86	17.80	7.16
p	< .001	< .001	< .001
Q	252.11	294.54	585.10
I^2	82.95	95.25	99.83
95% Lower limit	.60	.71	.46
95% Higher limit	.74	0.88	.90

animation, podcasts, learning objects, and videoconferences to complement, enrich, and transform education for better. In this category, we included specialized software, serious games, and web-based resources.

B. Traditional Lectures: it refers to curriculum-based and lecture-based teaching. This approach represents a concept of "knowledge as a content" provided by the teacher and includes paper-based exercises, textbooks, and lectures.

C. Traditional Pedagogical Tools: it refers to traditional educational resources (no multimedia resources) that teachers use to complement their lectures. It includes laboratory resources, math manipulatives, toys, and other didactic resources.

Results from Table 4 show that using AR technologies is more effective than using other pedagogical strategies, including other technological resources, traditional lectures, and traditional pedagogical resources. Therefore, the improvement in student scores seems to be related to the use of AR and not only to the intervention.

3.3. RQ3: how does the effect of AR vary according to the learning environment?

To evaluate the impact of AR systems according to the learning environment, we classified the studies according to three categories: formal settings, informal settings, and unrestricted settings. Table 5 summarizes the ES path coefficients for all the studies per learning environment.

Following Cohen's classification (1988), we can conclude that AR has a large effect on students' learning gains when the treatment is conducted in Informal settings. On the other hand, the effect is medium when treatments are conducted in Formal settings or a combination of formal and informal settings (unrestricted settings). However, the number of studies conducted in unrestricted settings is too low and the results could suffer from random noise and publication bias.

3.4. RQ4: what is the impact of AR applications according to the level of education?

We used the nine levels of education proposed by the UNESCO (2011) to evaluate the impact of AR systems according to the target group of each study. Table 6 presents the studies per level of education and Table 7 summarizes the ES path coefficients for all the studies per level of education.

Results in Table 7 indicates that AR has a large effect on *Bachelor's or equivalent level* and a medium to large effect on *Short-cycle tertiary education*. On the other hand, the effect was found to be medium on *Primary education and Secondary education*. However, it is important to note that the small sample in some target groups makes the results less reliable. None of the selected studies included *Early childhood education, Post-secondary non-tertiary education* or *Postgraduate education* as target groups.

3.5. RQ5: what is the impact of AR applications according to the field of education?

We used the ten broad fields of education proposed by the UNESCO (2011) to evaluate the impact of AR systems according to domain subject of each study. Table 8 presents the studies per broad field of education and Table 9 summarizes the ES path

Table 6
Summary of studies per level of education (target groups).

Level of education	# of studies
Early childhood education (ECE)	0
Primary education (PE)	19
Lower secondary education (LSE)	13
Upper secondary education (USE)	12
Post-secondary non-tertiary education (PSNTE)	0
Short-cycle tertiary education (SCTE)	2
Bachelor's or equivalent level (BEL)	18
Master's or equivalent level (MEL)	0
Doctoral or equivalent level (DEL)	0

Table 7
Summary of moderator analysis per level of education (target groups).

Variable	PE	LSE	USE	SCTE	BEL
K	19	13	12	2	18
N	1207	1052	1053	93	1300
d	.69	.59	.56	.78	.83
Z	17.38	15.55	11.74	3.11	21.59
p	< .001	< .001	< .001	< .001	< .001
Q	274.11	256.88	316.60	1.62	265.44
I^2	93.80	96.11	96.53	23.32	93.60
95% Lower limit	.61	.52	.46	.57	.76
95% Higher limit	.76	.67	.65	.99	.91

Table 8
Summary of studies per field of education (domain subject).

Broad Field	# of studies
Natural sciences, mathematics and statistics (NSMS)	32
Arts and humanities (AH)	11
Social sciences, journalism and information (SCJI)	5
Engineering, manufacturing and construction (EMC)	5
Information and communication technologies (ICT)	3
Health and welfare (HW)	7
Education (E)	1
Business, administration and law (BAL)	0
Agriculture, forestry, fisheries and veterinary (AFFV)	0
Services (S)	0

Table 9
Summary of moderator analysis per field of education (domain subject).

Variable	NSMS	AH	SCJI	EMC	ICT	HW	E
K	32	11	5	5	3	7	1
N	2568	745	320	176	237	577	116
d	.62	.82	.75	1.24	.39	.61	0.27
Z	16.21	18.05	12.28	29.60	2.47	8.07	.80
p	< .001	< .001	< .001	< .001	.01	< .001	.21
Q	268.41	305.59	450.49	286.36	82.07	482.84	0.00
I^2	89.20	96.73	99.33	98.95	99.63	98.76	0.00
95% Lower limit	.55	.73	.61	1.15	.24	.45	-.38
95% Higher limit	.70	.91	.89	1.32	.54	.77	.90

coefficients for all the studies per broad fields of education.

According to the found *d* values, we can assume that AR has a very large effect on *Engineering, manufacturing and construction* and a large effect on *Arts and humanities*. Likewise, the effect was found to be medium for *Social sciences, journalism and information*, *Natural sciences, mathematics and statistics* and *Health and welfare*. In contrast, the study revealed a small effect on the broad fields of *Information and communication technologies* and *Education*. However, it is important to note the small sample of some target groups may yield less reliable results. None of the selected studies included *Business, administration and law*, *Agriculture, forestry, fisheries and veterinary*, and *Services* as field of education.

4. Discussion

The main finding of this study is that AR favors the learning gains of students. The *d* value found in this meta-analysis ($d = .68$) is a little higher than the values found in the studies by Tekedere and Göker ($d = .67$) (2016), Garzón et al. ($d = .64$) (2019), Santos et al. ($d = .56$) (2014), Ozdemir et al. ($d = .51$) (2018), and Yilmaz and Batdi ($d = .36$) (2016). The higher *d* value in our meta-analysis can be explained by the inclusion of a larger sample, as well as the integration of three different research designs. However, with the exception of the study by Yilmaz and Batdi (2016), the conclusion is the same: AR has a medium effect on students' learning gains, which implies that AR has a positive impact on education. Further, we found a significant variability in the ES's of samples, which suggests the need to look for moderating variables. The analysis of variables such as *control treatment*, *level of education*, and *field of education* is important to detect the possible effects of different study features. Similarly, the analysis of the *learning environment* is important to identify how the design of the intervention influence the impact of AR on student's learning outcomes.

The mean $d = .68$ of AR on students' learning gains found in this meta-analysis must be interpreted carefully. Although the overall result is promising, we must consider that the results in individual studies may vary depending on a wide range of factors. Factors such as control treatment, learning environment, learner type, domain subject, and others that could not be considered in this study like learning methodology, intervention duration, computer attitude, and other characteristics of instructional design, influence the results of each intervention. Therefore, these results indicate that under certain conditions, AR has a positive impact on education.

4.1. Control treatment

In their study, Santos et al. (2014) recommended that future work should include measurement of the learning that can be attributed specifically to AR. However, none of the previous meta-analysis on the effectiveness of AR on education has performed such an analysis. In an attempt to bridge this research gap, we compared AR applications, as a pedagogical resource, with other types of pedagogical resources including multimedia resources, traditional lectures, and traditional pedagogical tools.

The ES of AR applications compared to multimedia resources was found to be $d = .67$. When comparing AR applications with traditional lectures the ES was $d = .62$. Finally, the ES was found to be $d = .61$ when comparing AR applications with traditional pedagogical tools.

Additionally, we compared the ES found in our meta-analysis with the ES's of meta-analyses on the effectiveness of other technologies on education. Merchant et al. (2014) analyzed the effectiveness of virtual reality on students' K-12 and higher education. They considered three experimental treatments: games, simulations, and virtual worlds and the ES's found were $d = .51,\ d = .41,\ and\ d = .41$, respectively. Chauhan (2016) performed a meta-analysis to measure the impact of technology on learning effectiveness of elementary students. She found an ES of $d = .54$ and concluded that technology leads to effective learning of elementary students. Finally, Tamim, Bernard, Borokhovski, Abrami, and Schmid (2011) conducted a second-order meta-analysis that included 25 first-order meta-analyses of the effectiveness of technology on education. They found a mean ES of $d = .34$ and concluded that technology has a low to moderate impact on education. In summary, we compared the d value found in our meta-analysis with the d values found in previous meta-analyses on the effectiveness of technology on education. This analysis suggests that although different types of technology have a positive impact on education, AR technologies seem to have a greater impact on the learning gains of students.

4.2. Learning environment

Informal settings involving activities outside of classrooms and laboratories produce better learning outcomes ($d = .80,\ \ p < .01$) than formal settings ($d = .67,\ \ p < .01$) within classrooms and laboratories. None of the previous meta-analysis on the effectiveness of AR on education performed a similar analysis. However, our finding supports the conclusions by previous qualitative studies (Chen & pingWang, 2015; Dunleavy, Dede, & Mitchell, 2009; Garzón, Acevedo, Pavón, & Baldiris, 2018; Sommerauer & Müller, 2014). Consequently, this suggests that teachers should be encouraged to increase the number of informal activities rather than just applying AR applications inside classrooms and laboratories. A combination of both formal and informal settings, present a medium ES ($d = .68,\ \ p < .01$) on learning outcomes. However, the sample size is too low and, thus the results are less reliable.

4.3. Level of education

The most important findings are that AR has a large effect on the learning gains of *Bachelor or equivalent level* and a medium to large effect on *Short-cycle tertiary education.* Ozdemir et al. (2018) conducted a moderator analysis to identify the impact of AR on student learning gains per target groups. Contrary to our findings, they concluded that there are no significant differences in the impact of AR according to the level of education. However, as they noted, their study included a very small sample and, as a result, their results may suffer from sample noise (Gurevitch et al., 2018). Our results suggest a greater impact of AR on more mature students of universities and vocational colleges compared to younger students of primary or secondary education. Issues such as the complexity of using the systems, multitasking, and information overload can affect young users of AR applications (Akçayir & Akçayir, 2017; Garzón et al., 2019; Radu, 2014). Although the effect of AR on learning gains in primary education and secondary education was found to be medium, the aforementioned issues can prevent these students from obtaining better results. In contrast, more mature students seem to be more engaged to the technology, which favors the learning process.

4.4. Field of education

The most striking result is that AR has a very large effect on *Engineering, manufacturing and construction.* None of the previous meta-analysis on the effectiveness of AR on education performed a similar analysis. We revised meta-analyses on the effectiveness of other technologies on education. We found that Chauhan (2016) analyzed the effect of technology on different fields of education and concluded that the effect is medium for all domain subjects. Similarly, Freeman et al. (2014) found that active learning (learning that includes technology as a pedagogical support) has a medium effect ($d = .47$) on subjects related to *Science*, *Engineering*, and *Mathematics*. In some fields of education such as pure sciences and social sciences, theoretical knowledge seems to prevail over practical knowledge. On the other hand, in the field of engineering, theoretical knowledge is directly connected to practice. Some authors claim that engineering learning is favored by constructivist methodologies that promote interactive learning environments where students can develop their ability to modify elements, generate ideas, and conduct experiments (Karabulut-Ilgu, Jaramillo, & Jahren, 2018; L.; Moreno, Gonzalez, Castilla, Gonzalez, & Sigut, 2007). Wojciechowski and Cellary (2013) concluded that AR favors the implementation of a constructivist methodology because it supports immersive and experiential learning, as well as cognitive development. These elements seem to sustain the very large effect of AR when used to learn engineering topics, which may imply the validity of the development of AR applications to support the learning of these subjects. Another outstanding result is that AR has a large effect on the broad field of *Arts and humanities.* However, it is important to mention that 82% of the applications in this field (in our meta-analysis), were intended to teach languages. Some studies state that perhaps the most important element to learn a second language is motivation (Solak & Cakir, 2015; Ushioda & Zoltán, 2017). Previous qualitative studies (Bacca et al., 2014; Diegmann, Schmidt-Kraepelin, Eynden, & Van DenBasten, 2015; Hung, Chen, & Huang, 2016; Mekni & Lemieux, 2014; Radu, 2014) state that after learning gains, motivation is the second most reported advantage of AR in education. This may explain the positive results of applying AR to teach a second language and poses new challenges for developers and practitioners.

4.5. Implications for theory

The analysis of the characteristics of the intervention is very important to understand the effect of AR on education. Perhaps, the most important intervention characteristic is the learning method. Some authors have stated that the characteristics of pedagogy tend to prevail over technology, that is, technology has no effect on learning by itself (Clark, 1994; Watson, 2001). These authors have pointed out that it is the instructional strategies (learning method), which create the conditions necessary to accomplish the purpose of learning. In contrast, other studies have pointed out that technology offers unique attributes that can affect both learning and motivation (Kozma, 1994; Schacter & Fagnano, 1999). The debate of whether technology affects learning or not has never been resolved and maybe never will be. In an attempt to tone down the dilemma, Hastings and Tracey (2005), concluded that both instructional methods and delivery medium must be aligned to facilitate learning. In line with this thought, Grace and Ratcliffe (2002) declared that although it is clear that technology plays an important role in learning processes, the way students feel about knowledge (emotions), moderates student performance more strongly than scientific reasoning or the delivery medium. Consequently, we believe it is relevant that developers, teachers, and policymakers consider not only the technological aspects of AR applications but also instructional strategies to take full advantage of this technology for education.

4.6. Implications for practice

Technology used for engaging with AR has changed specially since 2010 (Akçayir & Akçayir, 2017; Garzón et al., 2019; Martin et al., 2011; H.; Wu et al., 2013). Early AR projects tended to use specialized and expensive technology such as head-mounted display and head-up display. Instead, most recent projects use smartphones and tablets that provide all kind of services, enabling AR to become more personal and accessible by students. Accordingly, organizations and universities are investing large amounts of money in the development of AR technology to support learning (Bitter & Corral, 2014). However, applications of AR for education have been designed according to the specific needs and likes of developers and practitioners. Each application considers specific display devices, to teach different domain subjects, to different learner types, and the interventions are carried out in different contexts. Previous studies have described these variables through the narrative. Our study shows how the effect of AR differs in each specific context, thus providing stakeholders with valuable information to take into account for future developments.

5. Publication bias

Meta-analyses studies may be affected by the publication bias derived from multiple aspects (Egger, Smith, Schneider, & Minder, 1997). A common problem in research is that null-effects are barely published because such papers often are rejected. To evaluate the confidence of the results, we performed two types of analysis that assess whether the results were affected by publication bias: the fail-safe number and the Trim and Fill method. Fail-safe number is a procedure to evaluate whether publication bias (if it exists) can be safely ignored (Rosenthal, 1979). We calculated the fail-safe number to indicate the number of nonsignificant ES's of unpublished studies that would be required to reduce the total ES to insignificance. Fail-safe number is considered to be robust if it is larger than $5k + 10$, where k is the original number of studies included in the meta-analysis. If the fail-safe number is robust, it can be considered that the estimated ES of unpublished studies is unlikely to affect the overall ES. The fail-safe number for this meta-analysis was found to be 13257 at the significance level $\alpha = .05$, following Rosenthal's procedure (Rosenthal, 1991). This value is larger than $5n + 10$, which suggests that the publication bias is unlikely to be a problem. In addition, analysis of funnel plots (Trim and Fill method) also supports a lack of publication bias (see Fig. 2).

A funnel plot depicts the ES against the precision with which it is estimated (Duval & Tweedie, 2000). If there is no publication bias, the dots (representing the studies) are expected to be distributed on both sides of the vertical line (representing the average ES). If any study is outside the pyramid, it is expected to be located in the middle and upper parts of the figure. In case there is publication bias, most of the dots are located at the bottom of the funnel or only in one side of the vertical line (Borenstein, Hedges, Higgins, & Rothstein, 2010). We can observe in Fig. 2 that all the studies are symmetrically distributed on both sides of the vertical line. Four of the studies are located outside the pyramid, but they are located in the middle part of the figure. Therefore, we can confirm the absence of publication bias.

5.1. Limitations of the study

This meta-analysis included journal papers published in the three major bibliometric databases. However, future research should

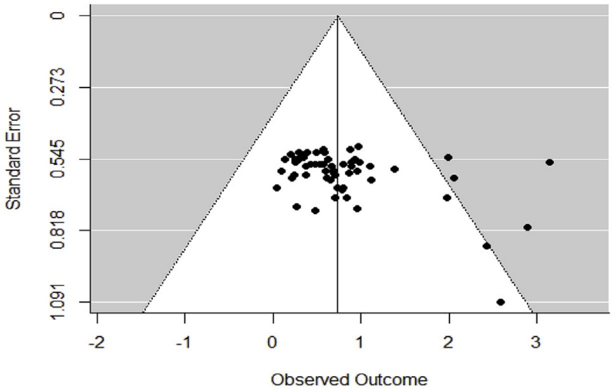

Fig. 2. Funnel scatter graphic (Trim and fill method).

include not only journal papers but also conference papers, doctoral dissertations, editorials, and reviews. It would also be interesting to consider other databases such as ProQuest, ScienceDirect, or JSTOR, and extend the search to languages other than English. In addition, although publication bias was found unlikely to be a problem for this meta-analysis our findings may be influenced by the fact that studies with insignificant results often are rejected. Therefore, the inclusion of such studies could vary the overall ES found in this meta-analysis. Moreover, the eligibility protocol excluded papers that did not provide enough information to calculate the ES. Hence, those studies could also potentially modify the results of the meta-analysis.

6. Conclusion

The objective of this meta-analysis was to integrate the findings of multiple independent studies to identify how AR systems influence students' learning outcomes. Based on the results of the meta-analysis of 64 research papers, we draw, as a general statement, that AR has a medium effect on students' learning gains. We compared AR applications, as a pedagogical resource, with other types of pedagogical resources including multimedia resources, traditional lectures, and traditional pedagogical tools. The results of this comparison indicate that the learning gains are higher when the intervention involves AR resources. Furthermore, there are certain conditions that moderate the effect of AR on the learning gains. The results indicate that the intervention is more effective when carried out in informal settings. Regarding the level of education, *Bachelor or equivalent level* students seem to benefit the most from AR. Likewise, AR systems show a higher impact when used to teach subjects related to *Engineering* and *Arts and Humanities*. The search protocol did not consider a time span; however, we could not find any studies before 2010 that met our inclusion criteria. This suggests that although AR dates back to the early 1990's, AR applications for education began to be significant only from 2010.

6.1. Considerations for future research

- We could not find evidence of the use of target groups such as *Early primary education*, *Post-secondary education* and *Postgraduate education.* Likewise, none of the studies in the meta-analysis included fields of education such as *Business, administration and law*, *Agriculture, forestry, fisheries and veterinary*, nor *Services.* Hence, given the apparent benefits of the implementation of AR systems in education, future investigation should be oriented towards the development of AR systems focused on those missing target groups and fields of education.
- This study analyzed the moderating effect of some variables that have been identified as important in this study and in previous studies. However, future work should include other variables that are important to find other benefits of the implementation of AR systems in education. It would be interesting to compare the results of regular students with those of students with special needs (whether cognitive or physical) to establish what type of learners benefit most from this technology. Another important variable that could be meta-analyzed is "motivation". Motivation has been described by many studies as one of the most important advantages of AR systems in education. However, none of the meta-analysis that have been conducted so far (including this one) has considered this variable. Moreover, because of limitations in the data provided by the studies, we could not include other moderator variables such as type of augmentation, spatial competence, and attitudes toward technology. The analysis of these variables is important to understand the impact of AR on education and, therefore, we encourage researchers and practitioners to consider them for future research.
- Most of the experimental interventions with AR in education are relatively short, in our study, for example, 93% of the interventions lasted less than one month. This leads us to pose the possibility that the positive impact of AR on education may obey to a "novelty effect". Therefore, we highlight the need for longitudinal studies that identify changes in long-term memory to corroborate that students effectively appropriated knowledge.
- In the same line, it is important to identify the learning gains in relation to the learning theories.

Some studies argue that minimal guidance during instruction is not enough (Kirschner, Sweller, & Clark, 2006; Mayer, 2004; R.;

Moreno, 2004). Pure-discovery methods with minimal feedback are very common in AR interventions (Diegmann et al., 2015); however, this approach can lead to misconceptions or incomplete or unorganized knowledge. In contrast, the studies by Kirschner et al. (2006) and Moreno (2004) state that learning is more significant when students receive direct instructional guidance because it promotes changes in long-term memory. Consequently, it is important that future research identify how does AR according to the learning methodology (e.g., constructivist, discovery, problem-based, experiential, inquiry-based, direct instruction), to guide future AR interventions.

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10. Meta-analysis of the impact of Augmented Reality on the learning gains of students with special needs

Reference:

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0.9 (Q3)	33	24	0.195 (Q3)

Summary:

Previous literature reviews have indicated that despite the numerous advantages of using AR applications to improve teaching and learning processes, these applications have mostly been applied to specific target groups, somehow overlooking important groups such as students with special needs. Previous literature reports that only a few applications consider the special needs of specific users, which represents a step back in terms of social inclusion. Moreover, as far as we know, there are no studies that indicate that using this technology benefits the learning process of students with special needs or under what conditions AR should be used to complement their education.

In that sense, we conducted a meta-analysis to identify the impact of AR on the learning gains of students with special needs. The meta-analysis included 12 empirical studies published between 2010 and 2018 in scientific journals and conference proceedings. We considered four types of disabilities: vision impairment, deaf or hard of hearing, intellectual disabilities, and physical disabilities. The study also analyzed the learning methods that best benefit each specific type of student and what type of learning environment best fits AR interventions that include students with special needs.

Overall results indicate that AR has a large impact on students with special needs and, consequently, the effect size was found to be large for all the subcategories according to Cohen's classification. However, despite the apparent multiple benefits, the use of AR in special needs education is still too limited. Therefore, stakeholders have great opportunities to develop new and better systems that include all types of learners.

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Meta-analysis of the impact of augmented reality on the learning gains of students with special needs

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Background

Augmented Reality (AR) has become an important technology to support learning processes. Many literature reviews have shown the trends, advantages, opportunities, and challenges of this technology in educational settings. These reviews report that one of the most important challenges of AR in education is the limited number of AR applications that consider the special needs of students. However, although there is a claim for the inclusion of accessibility characteristics to address the special needs of users, no study has been conducted to identify the impact of AR on the learning gains of students with special needs. That is, no data show that using this technology benefits the learning process of students with special needs or under what conditions AR should be used to complement their education. Many studies have shown that AR technologies offer unique advantages that enrich the learning environment, advantages that could not be obtained without the help of technology. Consequently, we pose that these unique characteristics of AR have a large impact on special needs education. With the above background, this study proposes to identify the effect size of AR on the learning gains of students with special needs. Additionally, the study analyzes the influence of moderating variables related to the design of the intervention such as learning method, learning environment, and intervention duration

Method

We conducted a meta-analysis to identify the impact of AR on the learning gains of students with special needs. The meta-analysis included 12 empirical studies (N = 270) published between 2010 and 2018 in scientific journals and conference proceedings. In this study, students with special needs refer to students who have some type of disability. Accordingly, we considered four types of disabilities, namely, vision impairment, deaf or hard of hearing, intellectual disabilities, and physical disabilities. The moderating analysis seeks to identify under what conditions students with special needs can obtain the best of this technology for their education.

Key results

The overall effect size of AR on the learning gains of students with special needs was found to be $d = .75$, $p<.001$. Regarding the moderating variables, the constructivist learning method was found to be the most beneficial for students with special needs ($d = .81$, $p<.001$). Likewise, AR applications seem to be more effective when interventions are carried out in informal settings outside the classroom ($d = .79$, $p < .001$). Finally, the results indicate that longitudinal studies were more positive ($d = .78$, $p <.001$) than cross-sectional studies.

Conclusion

The results indicate that AR has a positive impact on the learning gains of students with special needs. The effect size was found to be large for all the subcategories according to Cohen's classification. However, despite the apparent multiple benefits, the use of AR in special needs education is still too limited. Therefore, stakeholders have great opportunities to develop new and better systems that include all type learners.

Keywords

Augmented Reality, Meta-analysis, Special needs education.

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Tweetable abstract

We conduct a meta-analysis on the impact of augmented reality on students with special needs. We considered four types of disabilities: vision impairment, deaf or hard of hearing, intellectual, and physical. The effect size was found to be large for all the subcategories.

11. How do pedagogical approaches affect the impact of Augmented Reality on education? Meta-analysis and research synthesis

Reference:

Garzón, J., Kinshuk, Baldiris, S., Pavón, J. (2020). How do pedagogical approaches affect the impact of Augmented Reality on education? Meta-analysis and research synthesis. *Educational Research Review, 31*, 1–19.

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6.962 (Q1)	11.4 (Q1)	38	3.216 (Q1)

Summary:

Our third specific objective proposes to identify the pedagogical strategies of AR interventions that best favor students' learning gains. Most of the previous studies failed to analyze the pedagogical approaches, somehow ignoring that the success of an intervention depends not only on the technical characteristics of the technology but also on the pedagogical strategies to implement them. In this study, we proposed to identify how the pedagogical approaches that accompany AR interventions influence the impact of AR on the learning gains of students. In addition, the study analyzed the influence of the learning environment and the intervention duration on the achievements of the students.

We conducted a meta-analysis of 46 quantitative empirical studies published between 2010 and 2019 in major journals. As a result, we identified that the highest impact was obtained when interventions employed the Collaborative learning approach. Besides, the findings indicate that AR interventions carried out in informal settings such as field trips or activities outside the classroom, tend to present better results compared to interventions conducted in formal settings.

Finally, the results indicate better results in interventions that lasted between one week and four weeks. Furthermore, the study provides recommendations for students, teachers, researchers, and policymakers, on how learning occurs in AR interventions, what factors influence it, and how they can get the best of this technology to improve the teaching and learning processes.

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How do pedagogical approaches affect the impact of augmented reality on education? A meta-analysis and research synthesis

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ABSTRACT

Augmented Reality (AR) is gaining popularity in educational processes due to its recognized efficacy for teaching and learning. Many studies have identified the trends, advantages, opportunities, challenges, and impact of this technology on education. However, most of the previous studies failed to analyze the pedagogical approaches, somehow ignoring that the success of an intervention depends not only on the technical characteristics of the technology but also on the pedagogical strategies to implement them. This study presents a quantitative meta-analysis of 46 empirical studies to identify, in the light of the learning theories, how pedagogical approaches affect the impact of AR on education. In addition, we analyzed the impact of moderating variables on students' learning outcomes in AR interventions. The results indicate that the highest impact was obtained when interventions employed the collaborative pedagogical approach. Based on the findings of this study, we provide insights for researchers and practitioners on what characteristics of AR interventions seem to benefit students' learning outcomes and how pedagogical approaches can be applied in various educational contexts, to guide the design of future AR interventions.

1. Introduction

Recent decades have witnessed the emergence of educational applications based on Augmented Reality (AR) to enrich teaching and learning processes. The term "Augmented Reality" appeared in the early 1990s (Caudell & Mizell, 1992) and has been defined as a blending between reality and virtuality (Akçayir & Akçayir, 2017). However, its relatively high cost did not allow wide dissemination until the advent of mobile devices and the consequent integration of AR into them (Garzón, Pavón, & Baldiris, 2019). This integration has led to an accelerated growth in the number of AR applications for education since 2010, providing new alternatives to improve educational settings (Ozdemir, Sahin, Arcagok, & Demir, 2018).

Existing literature has identified the multiple benefits of including AR in education. As indicated by Garzón and Acevedo (2019), most of this literature correspond to qualitative reviews. These reviews have concluded that the inclusion of AR applications in education is relevant because they improve students' learning achievements and their motivation to learn. Table 1 presents some of the most cited qualitative reviews of AR in education from 2011 to 2019.

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Table 1
Qualitative reviews of AR applications in education.

Study	Studied variables	Main findings
Radu (2012)	Learning effects; advantages; disadvantages	AR increases content understanding. AR favors long-term knowledge retention. AR increases learning motivation.
Wu, Lee, Chang, and Liang (2013)	Learning effects; technological issues; pedagogical issues; learning issues	AR enables: ubiquitous, collaborative and situated learning; visualizing the invisible; and bridging formal and informal learning.
Bacca, Baldiris, Fabregat, Graf, and Kinshuk (2014)	Advantages and disadvantages; field of education, level of education	The main advantages of AR in education are learning gains and motivation. The main difficulty is maintaining superimposed information.
Diegmann, Schmidt-Kraepelin, Eynden, and Basten (2015)	Benefits of AR in education	AR favors content understanding, language association, and physical task performance.
Akçayir and Akçayir (2017)	Advantages and disadvantages; field of education, level of education	The main advantage of AR in education is learning gains. The most reported challenge is the difficulty for students to use it.

These reviews expose the main findings of the literature, furthering the understanding of the status, trends, advantages, challenges, and opportunities of AR technology in education. There are also quantitative reviews that have been conducted to analyze the influence of AR on education. One of the most common types of quantitative reviews in social and behavioral sciences is meta-analysis (Hedges & Olkin, 1985). Meta-analyses comprehend the statistical analysis of a large amount of data collected from individual studies in order to integrate the findings of the studies (Glass, 1976). Meta-analyses increase the power of analysis, by proceeding from particular observations to general statements. The particular observations derive in the estimation of the effect size (ES) that characterizes the magnitude of the experimental effect in each study. On the other hand, the general statements are derived from the analysis of the overall ES that is estimated when the results of the individual studies are integrated (Garzón & Acevedo, 2019).

To our knowledge, five quantitative meta-analyses of the impact of AR on education have been conducted to date (see Table 2). These meta-analyses used standard deviations, mean scores, and sample sizes to calculate the Cohen's *d* ES (Cohen, 1992). Further, these studies analyzed moderating variables to provide complete information regarding the uses of AR in education.

These meta-analyses identified the impact of AR on the learning gains and the effect of some moderating variables on the impact of AR on education, somehow stating that AR has effectively taken root in education. However, none of the previous studies included the pedagogical approaches as a research variable, nor did they present any findings regarding the pedagogical strategies to be implemented in AR interventions. Pedagogical approach refers to the method that teachers use to deliver the knowledge so that students engage in the learning process (Schunk, 2012). The lack of formal pedagogical approaches when applying AR to learning activities tends to confuse and frustrate students (Liu & Chu, 2010). In this sense, the studies by Turan, Meral, and Sahin (2018) and Garzón and Acevedo (2019) suggested that future research should examine the impact of the integration of different pedagogical strategies in AR interventions.

One of the most famous and enduring debates in the field of instructional technology is the Clark/Kozma debate. This debate focused on the role of media in the learning process and has been a constant point of contention for decades (Sickel, 2019). Clark (1994) stated that technology has no influence on learning per se. He claimed that technology, as well as other media, are mere vehicles of information and, in contrast, pedagogical strategies are responsible for achieving the purpose of learning. Oppositely, Kozma (1994) argued that technology offers unique advantages that enrich the learning environment, advantages that could not be obtained without the help of this media. The debate about whether it is the technology or the learning method the main character in the learning process will continue and perhaps will never be resolved. Nevertheless, we pose that AR interventions in education should consider both the technical characteristics and the pedagogical strategies to obtain the best of this technology to improve student learning.

2. Fundamentals of the pedagogical approaches

There is no single definition of learning that is universally accepted by theorists, researchers, and practitioners. However, a broadly accepted statement indicates that learning implies a change in human behavior, knowledge, skills, beliefs, and attitudes (Schunk, 2012). Theoretical traditions have set four major learning theories: Behaviorism, Cognitivism, Humanism, and

Table 2
Summary of meta-analyses of AR in education.

Author	N	d	Moderator analysis
Santos et al. (2014)	7	.56	Display device, software libraries.
Tekedere and Göker (2016)	15	.67	Grade level, field of education.
(Z. Yilmaz & Batdi, 2016)	12	.36	Cognitive domain.
Ozdemir et al. (2018)	16	.51	Grade level, display device, sample size.
Garzón and Acevedo (2019)	64	.68	Grade level, field of education, control treatment.

Constructivism (Schunk, 2012). Nonetheless, evidence from the literature shows that Constructivism is the most popular learning theory in educational technology (Anderson, 2016; Duffy & Jonassen, 2013).

Constructivism is an approach to learning that states that people actively construct knowledge and that reality is determined by the learner's experience (Paige, 1996). There are several principles related to constructivism as a theory for teaching and learning. In this sense, we highlight four principles that are key to understanding the importance of constructivism in educational technology. First, the central idea of constructivism is that knowledge is not transmitted from the teacher to the student but is an active process of construction (Schunk, 2012). This implies that students construct new knowledge on top of their prior knowledge and that prior knowledge influences the new knowledge that a learner will construct from new learning experiences. This is especially important in the context of engineering because, in it, practical knowledge is constructed on the basis of theoretical foundations (Taajamaa, Järvi, Laato, & Holvitie, 2018). Second, another important notion of constructivism is that learning is an active rather than a passive process. A passive view of teaching sees the learner as an empty vessel that must be filled with knowledge, while constructivism holds that learners construct meaning through active engagement with the environment (K. Yilmaz, 2008). Third, learning is a social activity (Palincsar, 1998). The social world of a learner includes the people that influence the learner's life, such as family, friends, teachers, policymakers, and others. This social environment plays a central role in the construction of meaning by the learner, and thus, learning can be described as a collaborative process. Fourth, although learning is described as a social activity, all knowledge is personal, that is, each individual learner has a distinctive point of view, based on existing knowledge and previous experiences (Fox, 2001). This means that same activities, teaching methods, and lessons may result in different learning by each student, because their interpretations of things and ideas may differ.

Constructivism is typically divided into three broad categories, namely cognitive constructivism, social constructivism, and radical constructivism. Cognitive constructivism is based on Jean Piaget's theory of cognitive development, which focuses on how humans make meaning in relation to the interaction between their experiences and their ideas (Piaget & Cook, 1952). Social constructivism is based on the work of Lev Vygotsky, which stresses the fundamental role of social interaction in the development of cognition (Vygotsky, 1978). Unlike Piaget's idea that children's development precedes their learning, Vygotsky argued that social learning tends to precede development. Finally, radical constructivism is based on the work of Ernst von Glasersfeld who states that all knowledge is constructed rather than perceived through senses (Von Glasersfeld, 1974). Radical constructivism emphasizes the experiences of learners, differences between learners, and the importance of uncertainty. In contrast to social constructivism, radical constructivism maintains the idea that humans cannot overcome their limited conditions of perception.

There is a significant number of approaches to learning that derive from the principles of constructivism; however, the most common pedagogical approaches in AR interventions are Collaborative learning, Inquiry-based learning, Situated learning, Project-based learning, and Multimedia learning (Saltan & Arslan, 2017; Wen & Looi, 2019). All these approaches implement similar strategies in educational interventions, such as considering students as the protagonists of the learning process, using scaffolding, including various learning scenarios, considering high thinking skills, and focusing on real problems. Nonetheless, each approach has unique characteristics that give it its place in the pool of learning approaches. The subsequent sub-sections present brief definitions of each of these pedagogical approaches and list their main characteristics.

2.1. Collaborative learning (CL)

This approach describes situations in which particular forms of interaction among people are expected to occur, triggering learning mechanisms. To increase the possibility of interactions occurring, Dillenbourg (1999) proposes the following four strategies: 1) to set up initial conditions, 2) to specify the role of each collaborator, 3) to specify interaction rules for face to face collaboration, and 4) to monitor and regulate the interaction. This approach is based on Vygotsky's notion of the social nature of learning, which basic idea is to promote learning in ways that are not possible with highly competitive learning models (Adams & Hamm, 2019).

One of the most notorious affordances of CL in educational technology is that it decreases the cognitive load. Cognitive load theory is based on the premise that the cognitive structure of the human brain allows a limited amount of information to be processed (Van Merrienboer & Sweller, 2005). This situation is potentially problematic in individual learning processes. Alternatively, CL proposes the equitable division of tasks among learners, which reduces the amount of information each learner must process.

Collaborative environments involve strategies regarding group size, learning goals, communication, assignments, and assessment. Regarding group size, it is important to establish medium-sized groups of 4–5 students. Smaller groups lack diversity and may limit divergent thinking, in contrast, larger groups risk not all members participating in the activities. Additional to this, it is important to set concrete group goals before beginning an assignment, as this keeps the group focused on the activity and establishes a common purpose. As for communication, collaborative environments should promote interpersonal communication to build trust that allows dealing with emotional issues that arise during the learning process. Similarly, assignments should encourage group members to explain concepts thoroughly to each other, as students who provide and receive intricate explanations gain most from collaborative environments. Finally, collaborative environments should consider the learning process itself as a part of the assessment, since the quality of interpersonal discussions, the grade of student commitment, and the adherence to group norms, are effects of the learning process that are as important as the learning itself.

2.2. Inquiry-based learning (IBL)

Also known as *Discovery learning,* this is an active pedagogical approach that requires the student to search a problem, pose questions, and then search for possible solutions to those questions. In this approach, the teacher is a facilitator of knowledge and the student is the protagonist of the learning process (Edelson, Gordin, & Pea, 1999). This approach uses different strategies such as small group discussion and guided learning. Instead of memorizing facts and material, students learn by doing, which allows them to construct knowledge by exploration, experience, and discussion (Pedaste et al., 2015).

Adapted from the work by Lazonder and Harmsen (2016), next we describe some of the most important advantages of IBL in educational settings. 1) It increases learning experiences for students by allowing them to explore topics themselves. 2) It teaches skills needed for all learning areas because as they explore a topic, students construct critical thinking and communication skills. 3) It encourages curiosity in students, as it allows them to share their ideas on a topic. 4) It deepens students' understanding of topics because rather than simply memorizing facts, students make their connections about what they are learning. 5) It increases commitment with the material by allowing students to explore topics, make their own connections, and ask questions, which encourages them to fully engage in the learning process. 6) Perhaps one of the most notorious advantages of IBL in educational processes, is that it increases the motivation for learning. When students engage with the material in their own way, they not only gain a deeper understanding of the topics but develop a passion for exploring and learning.

2.3. Situated learning (SL)

This approach proposes that knowledge is related to social situations and that people must continuously interact with situations to gradually obtain useful knowledge. Brown, Collins, and Duguid (1988) were the first proponents of this approach. They argued that meaningful learning will only occur if it is embedded in the social and physical context within which it will be used. Within this approach, students are involved in cooperative activities where they are challenged to use their critical thinking and kinesthetic abilities to build new knowledge (Lave & Wenger, 1991).

This approach has been deeply rooted in educational technology because technology allows creating environments in which students can learn by doing. In addition, technology can be used without sacrificing the authentic context, which is a critical element of SL. McLellan (1994) summarizes the SL approach indicating that while knowledge must be learned in the context, the context may be the real work environment, a highly realistic or virtual substitute for the real work environment, or an anchoring context such as a those provided by information technologies.

2.4. Project-based learning (PBL)

This is a student-centered approach to learning, in which students gain knowledge and skills by working for an extended period to investigate and answer to a complex question, problem, or challenge (Blumenfeld et al., 1991). Within this approach, learners tend to have more autonomy over what they learn, maintaining interest and motivating them to assume greater responsibility for their learning (Worthy, 2000). In addition, PBL poses that it is important that learners not only solve problems in real-world contexts but also to allow them to witness the practitioners solving similar problems (Bell, 2010).

Adapted from the work of Vallera (2019), PBL includes following key elements for educational technology: 1) teach significant content through knowledge and skills, 2) require critical thinking, problem-solving, collaboration, and various forms of communication, 3) engage rigorous investigation, 4) create a need to know essential content and skills, 5) provide continuous feedback, and 6) have students present their final projects to a public audience.

For the context of our study, we unified the concepts of "Project-Based Learning" and "Problem-Based Learning" considering that there is no single distinction that is universally adopted, as they share more similarities than differences (Sindre, Giannakos, Krogstie, Munkvold, & Aalberg, 2018).

2.5. Cognitive theory of multimedia learning (CTML)

Also known as the "multimedia principle", this approach states that people learn more deeply from words and pictures than from words alone (Mayer, 2005). Nonetheless, to achieve multimedia learning it is not enough to simply add words to the pictures. Thus, the purpose of CTML is to offer instructional media according to how the human brain works. This approach is based on three main assumptions: a) there are two separate channels for processing information (auditory and visual); b) there is limited channel capacity; and, c) learning is an active process of filtering, selecting, organizing, and integrating information. Based on these theoretical assumptions, the CTML postulates principles for the design of effective multimedia instructions (Mayer, 2017).

Research by Neo and Neo (2009) indicates that multimedia can help students construct knowledge in a well-designed constructivist learning environment. Multimedia allows presenting text, graphics, video, animation, and sound in an integrated way to facilitate collaboration and provide an effective means to create and enhance constructivist approaches.

For the context of our study, we unified the concept of Game-Based Learning approach to CTML, considering that multimedia learning environments often include learning based on games to enhance the motivation of students. Moreover, Mayer (2002) proposes the implementation of games as an alternative to reduce cognitive load in multimedia environments, when the total cognitive processing load exceeds the learner's cognitive capacity.

The research by Martin-Gonzalez, Chi-Poot, and Uc-Cetina (2016) reported that most studies that include AR applications in education are limited to using the technology without integrating pedagogical approaches to enrich the educational process. They stated that this integration might take time considering that AR technology is still a new phenomenon for education. The time has passed since then and the number of studies that consider the design of AR interventions in the light of the pedagogical foundations is steadily increasing (Wen & Looi, 2019). The next section presents the research objectives of our study, which aim at identifying how do these pedagogical approaches affect the impact of AR on education.

3. Research objectives

With the above background, this study proposes to conduct a quantitative meta-analysis to contribute to the debate on the effect of AR in combination with pedagogical approaches, on students' learning outcomes. In particular, the study presents two research objectives:

1) Examine whether the pedagogical approach affects the impact of AR on students' learning outcomes.
2) Identify the impact of the learning environment and the intervention duration on students' learning outcomes in AR interventions.

Our meta-analysis differs from previous studies in three main aspects. First, this meta-analysis evaluates the pedagogical approaches of the interventions. Second, the sample sizes in previous meta-analyses have been relatively small, which may risk leading to wrong or non-conclusive interpretation of the results (Lipsey & Wilson, 2001). In this sense, our study follows the recommendations by Morris and DeShon (2002) to integrate studies with different research designs, which provide us with a larger sample. Third, we offer insights to researchers on how learning occurs in AR interventions, what factors influence learning in AR interventions, and how pedagogical approaches can be applied in educational contexts, to guide the design of future AR interventions.

4. Method

We conducted a quantitative meta-analysis following the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) (Moher, Liberati, Tetzlaff, & Altman, 2009). PRISMA promotes transparency, helps reduce potential bias and avoids duplication of reviews, resulting in an increase in both the quality of the reports and the methodological quality of meta-analyses. PRISMA is a set of consensus-based reporting guidelines that requires a meta-analyst to 1) collect studies, 2) code study features, 3) calculate the ES of each study, and 4) investigate moderating effects of study's characteristics.

4.1. Inclusion criteria

Taking into consideration the research objectives of this study, we defined concrete inclusion criteria to ensure a set of potentially relevant studies that allow conducting the meta-analysis. Accordingly, we defined that the studies included in the meta-analysis must meet the following criteria:

- The study measures the impact of AR on students' learning gains as an outcome variable.
- The study includes a control condition (pretest-posttest or control group-experimental group).
- The study provides enough information to calculate the ES.
- The study provides information on the pedagogical approach of the intervention.
- The study is written in English.

4.2. Search protocol

The first step was the selection of the educational databases to identify the primary studies. We focused our research on three major bibliometric databases, namely Web of Science, Scopus, and Google Scholar because they provide sufficient coverage stability to be used in systematic reviews (Harzing & Alakangas, 2016). We searched for scientific papers using the following keywords: *Augmented Reality*, *Augmenting Reality*, and *Mixed Reality* combined with *Education, Learning, Training,* and *Teaching*. Then, we scanned the previous meta-analyses of the impact of AR on education to locate relevant studies. The final search was carried out in December 2019, which resulted in 635 empirical studies.

Two of the researchers proceeded to carry out the inclusion/exclusion process as explained next. First, the title and the keywords of all the extracted papers were manually scanned to eliminate irrelevant studies. This process resulted in 382 studies. Then, the researchers read the abstract of each paper. This resulted in the elimination of documents other than papers, review papers, non-English papers, qualitative papers and papers that did not match the research objectives of this study. This process resulted in 150 papers. Next, the researchers read each paper to select those which met the inclusion criteria. Missing or unclear information in the studies was requested from the authors by email. If the information was not received in the following month, the paper was discarded. This process resulted in 46 papers. Further, the researchers scanned the reference list of each paper, but it did not result in the identification of any new relevant study. Finally, 46 studies were identified to be included in the meta-analysis. The search protocol did not consider a time span; however, we could not find any studies before 2010 that met our inclusion criteria. Cohen's kappa was used to verify the inter-coder reliability at each exclusion level (Cohen, 1992). Fig. 1 summarizes the search procedure that was followed to collect, assess, and analyze, the empirical evidence related to the research objectives.

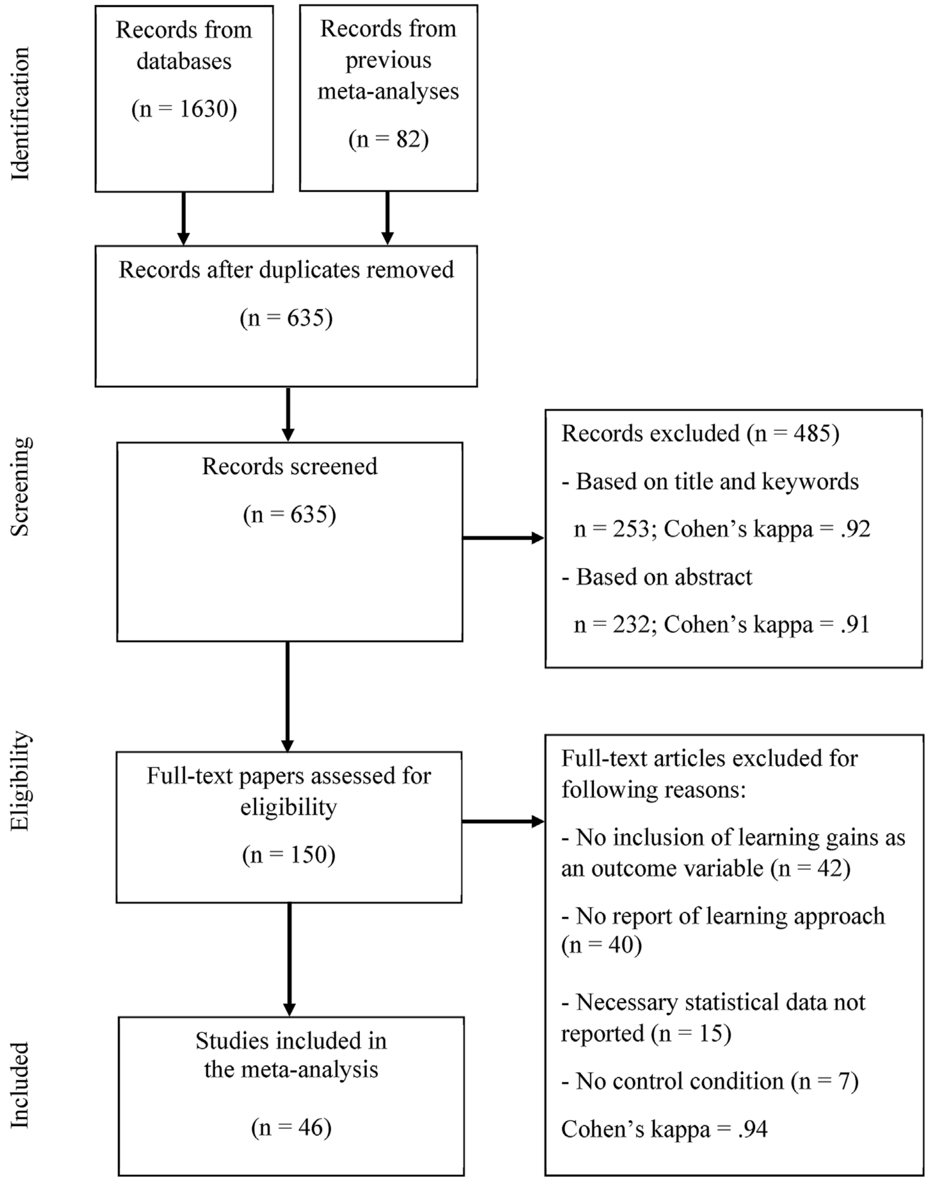

Fig. 1. PRISMA Flowchart for search protocol.

4.3. Coding the studies

The coding process was conducted by two different researchers, two experts in educational technology with more than 15 years of experience each. They read each paper individually and used the content analysis technique to extract the data, as recommended by Hsu, Hung, and Ching (2013). We designed a data form that included the following information: title, authors, year of publication, sample size, type of research design, pedagogical approach, learning environment, intervention duration, mean values and standard deviations, level of education, field of education, and additional space for observations. To measure the inter-rater reliability, we calculated Cohen's kappa statistic. This value was found to be 0.93 which corresponds to “almost perfect agreement” as stated by Cohen (1992). Occasional disagreements were discussed and resolved by consensus.

4.4. Calculation of the ES

The purpose of our meta-analysis is to synthesize the information from the studies to estimate the size of the effect of AR on student's learning gains, according to the pedagogical approaches in AR interventions. This meta-analysis integrates studies with different research designs, to provide a complete overview of the effect of the pedagogical strategies in AR interventions. This integration allowed us to accumulate a larger sample, which avoids sample noise that can lead to an incorrect or inconclusive interpretation of the results (Lipsey & Wilson, 2001). In that regard, this meta-analysis includes between-participants design studies and within-participants design studies. Between-participants design studies involve experimental and control treatments to measure the raw difference between treatments (raw-score metric). There are two types of between-participants design studies. First, the Pretest-Posttest-Control (PPC) that evaluates students before and after the treatment. Second, the Posttest Only with Control (POWC) that evaluates students only after the treatment. On the other hand, within-participants design studies consist of a Single Group Pretest-Posttest (SGPP) design. In this design, the students undergo only the experimental treatment and are evaluated before and after the treatment (change-score metric).

To identify how pedagogical approaches affect the impact of AR on education, we selected students' learning outcomes as the dependent variable in all the studies. We measured the ES of each study based on Cohen's d ES using means, standard deviations, and sample sizes. When a study provided several means and standard deviations, they were averaged and the average was used to calculate the overall ES (Bernard et al., 2004). The guidelines for interpreting the ES values were $d = .2$ (small effect), $d = .5$ (medium effect), $d = .8$ (large effect), $d = 1.2$ (very large effect), and $d = 2.0$ (Huge effect) (Cohen, 1992).

As recommended by Morris and DeShon (2002), we first calculated the ES of each study and second, we transformed each ES into a common metric for comparison. Following recommendations from Morris and DeShon (2002), to calculate the ES from between-participants design studies, we computed a separate ES within the control and experimental groups and then we used the difference between the two values to estimate the overall ES of the study (Becker, 1988). Moreover, to calculate the ES from within-participants design studies, we used the difference between the mean scores of the evaluations before and after the treatment (Hedges, 1982). Further, to transform each ES into a common metric, Morris and DeShon (2002) recommend determining which metric will be used as the common metric according to the purpose of the analysis. The purpose of this meta-analysis is to determine the extent of change attributable to the AR intervention through a specific pedagogical approach, hence, the raw-score metric better adapts to the study. Therefore, to transform a change-score metric ES into a raw-score metric ES, Morris and DeShon (2002) recommend using the equation $d_{BP} = d_{WP}\sqrt{2(1-\rho)}$, where, d_{BP} is the transformed ES for the raw-score metric (between-participants design), d_{WP} is the ES for the change-score metric (within-participants design), and ρ is the correlation between scores. Additionally, to integrate between-participants design studies with within-participants design studies, meta-analysts must assume that experimental conditions had similar variance (Becker, 1988; Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Cohen, 1988; Garzón & Acevedo, 2019; Morris, 2008). According to Levene's test ($F = 2.20, \ p = .06$), the data in our meta-analysis do not show variations by more than five percent, and therefore, we assume that the variance of the scores is homogeneous across time.

4.5. Moderator analysis

The moderator analysis aimed to identify whether the effect of the pedagogical approaches varied according to specific characteristics of the intervention. We based our moderator analysis on two important moderator variables that have been identified as moderators in previous studies of the impact of technology on education: the learning environment and the intervention duration. In addition, we performed a cross-analysis to identify the effect of these moderator variables depending on the field of education and the level of education in each study.

4.5.1. Learning environment

This moderator variable was considered to establish whether the effect of the pedagogical approaches differs depending on the context in which interventions are carried out: formal setting (FS) (classroom, laboratory), informal setting (IS) (field trips, museums, outdoor activities), or unrestricted setting (US) (including both FS and IS) (Chauhan, 2016).

4.5.2. Intervention duration

This moderator variable was analyzed to determine whether the effect of the pedagogical approaches differs depending on the duration of the AR intervention. We considered the four categories of time recommended by Chauhan (2016), namely, One day; > One day < one week; ≥ One week < one month; and ≥ One month.

5. Results

The main purpose of this meta-analysis is to identify how pedagogical approaches affect the impact of AR on education. Although the focus of this research is not to calculate the overall ES of AR on education, such analysis was performed to evaluate how the pedagogical approaches moderate the impact of AR on students' learning outcomes. Table 3 presents the main characteristics of each study, including the calculated ES and the values per each moderating variable.

The combined effect of the 46 studies was calculated using the random-effects model. Morris and DeShon (2002) suggest the assumption of this model when the studies are heterogeneous. We tested the homogeneity of the studies based on Cochran's Q, I^2 index, and *p-value*. Cochran's Q is a comprehensive test of heterogeneity when the number of studies is large, highlighting even small heterogeneity in meta-analyses. In our study, the Q value was found to be $Q = 148.63$, which is greater than the critical value for the 44 degrees of freedom at a 95% significance level from the Chi-square distribution table ($Q = 60.48$), indicating heterogeneity across the studies. Alternatively, the I^2 index describes the percentage of variations across the studies that is due to heterogeneity rather than chance. In our study, the percentage of heterogeneity was 71.07%, which indicates considerable heterogeneity. Finally, a low *p-value* as found in our study ($p < .01$), provides evidence of heterogeneity of the effects of the interventions. These three values led us to confirm the hypothesis of heterogeneity across the studies and support our assumption of the random-effects model. The overall effect

Table 3
Summary of the studies of the meta-analysis sorted by publication date.

Author	*d*	Learning theory	Learning Environment	Intervention duration
Liu and Chu (2010)	.78	CL	IS	≥ One month
Chen and Tsai (2012)	.27	SL	FS	One day
Enyedy, Danish, Delacruz, and Kumar (2012)	1.66	IBL	FS	≥ One week < one month
Chang and Liu (2013)	3.37	SL	IS	One day
Di Serio, Ibáñez, and Kloos (2013)	.67	PBL	FS	Three days
Lin, Duh, Li, Wang, and Tsai (2013)	.85	CL	FS	One day
Kamarainen et al. (2013)	.48	SL	IS	One day
Chang, Wu, and Hsu (2013)	.58	SL	FS	One day
Chiang, Yang, and Hwang (2014)	.84	IBL	FS	One day
Cai, Wang, and Chiang (2014)	.68	IBL	FS	One day
Sommerauer and Müller (2014)	1.03	CTML	IS	One day
Wang, Duh, Li, Lin, and Tsai (2014)	.79	CL	US	One day
Zhang, Sung, Hou, and Chang (2014)	.71	SL	FS	One day
Estapa and Nadolny (2015)	.32	SL	FS	One day
Schmitz, Klemke, Walhout, and Specht (2015)	.32	CL	FS	One day
Fonseca, Redondo, Villagrasa, and Canaleta (2015)	2.23	CL	FS	One day
Ke and Hsu (2015)	.79	CL	IS	One day
(M. T. Cheng, Lin, & She, 2015)	.36	SL	FS	One day
Chang, Hou, Pan, Sung, and Chang (2015)	1.71	SL	IS	One day
Tarng, Ou, Yu, Liou, and Liou (2015)	.89	SL	IS	One day
Ibanez, Di Serio, Villaran, and Delgado Kloos (2016)	.32	IBL	FS	One day
Huang, Chen, and Chou (2016)	1.01	PBL	IS	One day
Akçayir, Akçayir, Pektaş, and Ocak (2016)	.64	CTML	FS	≥ One month
Küçük, Kapakin, and Göktaş (2016)	.67	CTML	FS	One day
Tarng, Lin, Lin, and Ou (2016)	.51	SL	IS	≥ One month
Hsiao, Chang, Lin, and Wang (2016)	.68	IBL	FS	≥ One month
Cai, Chiang, Sun, Lin, and Lee (2017)	.54	IBL	FS	One day
(T. C. Hsu, 2017)	.75	SL	FS	One day
Joo-Nagata, Martinez Abad, García-Bermejo Giner, and García-Peñalvo (2017)	.91	CTML	IS	One day
Widiaty, Riza, Danuwijaya, Hurriyati, and Mubaroq (2017)	.61	SL	FS	Not specified
Hwang and Chen (2017)	.44	IBL	IS	≥ One week < one month
Cascales-Martínez, Martínez-Segura, Pérez-López, and Contero (2017)	.27	IBL	FS	≥ One week < one month
Efstathiou, Kyza, and Georgiou (2017)	.90	SL	IS	One day
Aebersold et al. (2018)	.64	SL	IS	One day
Wang, Huang, Liao, and Piao (2018)	.80	CTML	FS	One day
Tarng, Ou, Lu, Shih, and Liou (2018)	.91	SL	FS	≥ One month
Turan et al. (2018)	1.03	CTML	FS	≥ One week < one month
Chang and Hwang (2018)	.26	PBL	FS	≥ One month
Wu, Hwang, Yang, and Chen (2018)	.94	SL	FS	One day
Chao and Chang (2018)	.43	CTML	FS	≥ One month
Sirakaya and Cakmak (2018)	.69	CTML	FS	≥ One week < one month
Lai, Chen, and Lee (2019)	.73	CTML	FS	One day
Barmaki et al. (2019)	.32	CL	FS	One day
Bursali and Yilmaz (2019)	.84	PBL	FS	≥ One month
Vallera (2019)	.78	PBL	FS	≥ One month
Fidan and Tuncel (2019)	1.50	PBL	FS	≥ One month

Note. We excluded the study by Chang and Liu (2013) because its unusually huge ES of $d = 3.37$ is likely to bias the overall ES calculation (Lipsey & Wilson, 2001).

of all the studies according to the learning gains of the students is shown in Fig. 2.

The overall Cohen's d ES was found to be $d = 0.72$, which indicates that AR has a medium ES on student's learning gains.

5.1. Impact of pedagogical approaches on students' learning outcomes

Our first research objective aims to identify the effect of the pedagogical approaches on the learning outcomes of students. To achieve this objective, we grouped the studies according to the pedagogical approach that accompanied each intervention (see Fig. 3). In case a specific intervention included elements of different approaches, we identified the main approach in that specific intervention. It is important to mention that all the studies included in our meta-analysis fall into one of the five pedagogical approaches defined in section 2.

According to Fig. 3, the ES was found to be $d = 0.76$ for CTML; $d = 0.85$ for CL; $d = 0.73$ for IBL; $d = 0.74$ for PBL; and $d = 0.59$ for SL. These results suggest that learning outcomes could be more reliable on the SL approach and potentially, more beneficial on the CL approach.

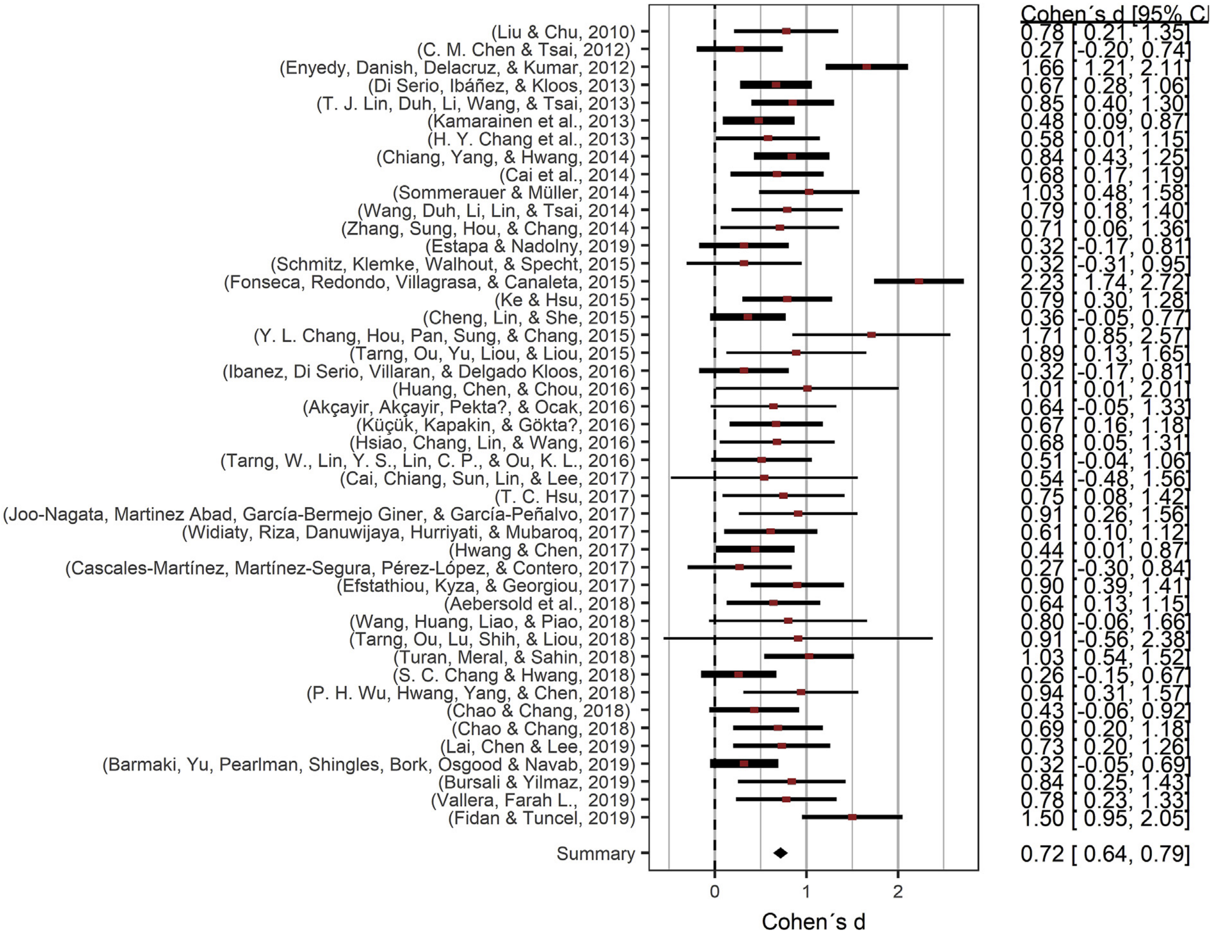

Fig. 2. Overall ES of AR on students' learning gains.

5.2. Impact of moderating variables on students' learning outcomes in AR interventions

Our second research objective aims to identify the impact of moderating variables on students' learning outcomes in AR interventions. As indicated by Lipsey and Wilson (2001), the heterogeneity of the studies suggests that it is appropriate to test for moderator variables. Next, we present the effect of the learning environment and the intervention duration as recommended in the study by Chauhan (2016), as moderator variables in AR interventions. Additionally, we performed a cross-analysis to identify the effect of the moderator variables depending on the field of education and the level of education in each study.

5.2.1. Learning environment

The analysis of the learning environment gives insights on what characteristics of the environment surrounding the learner creates a favorable learning setting. These environments can be formal (classrooms, laboratories) or informal (field trips, museums, outdoor activities). As shown in Fig. 4, we sorted the studies according to the learning environment in each study.

As depicted in Fig. 4, the effect was found to be $d = 0.71$ in FS and $d = 0.73$ in IS. There is only one study in the category US, and therefore, any conclusion would be biased. These results suggest a small advantage of performing AR interventions in informal environments outside of classrooms and laboratories.

5.2.2. Intervention duration

The analysis of the intervention duration is important to inform teachers and researchers on how long AR interventions should take, or what is the expected result given a specific duration. Fig. 5 reports the forest plot of the effect of each study according to the duration of each AR intervention.

As depicted in Fig. 5, the effect was found to be $d = 0.64$ in the "One day" category; $d = 0.95$ in the "$\geq$ One week $<$ one month" category; and $d = 0.69$ in the "$\geq$ One month" category. There is only one study in the "$\geq$ One day $<$ one week" category with a $d = 0.67$; therefore, this value is not reliable. These results suggest a significant advantage of designing AR interventions that last between one week and four weeks and that any other intervention duration category has no significant differences in learning

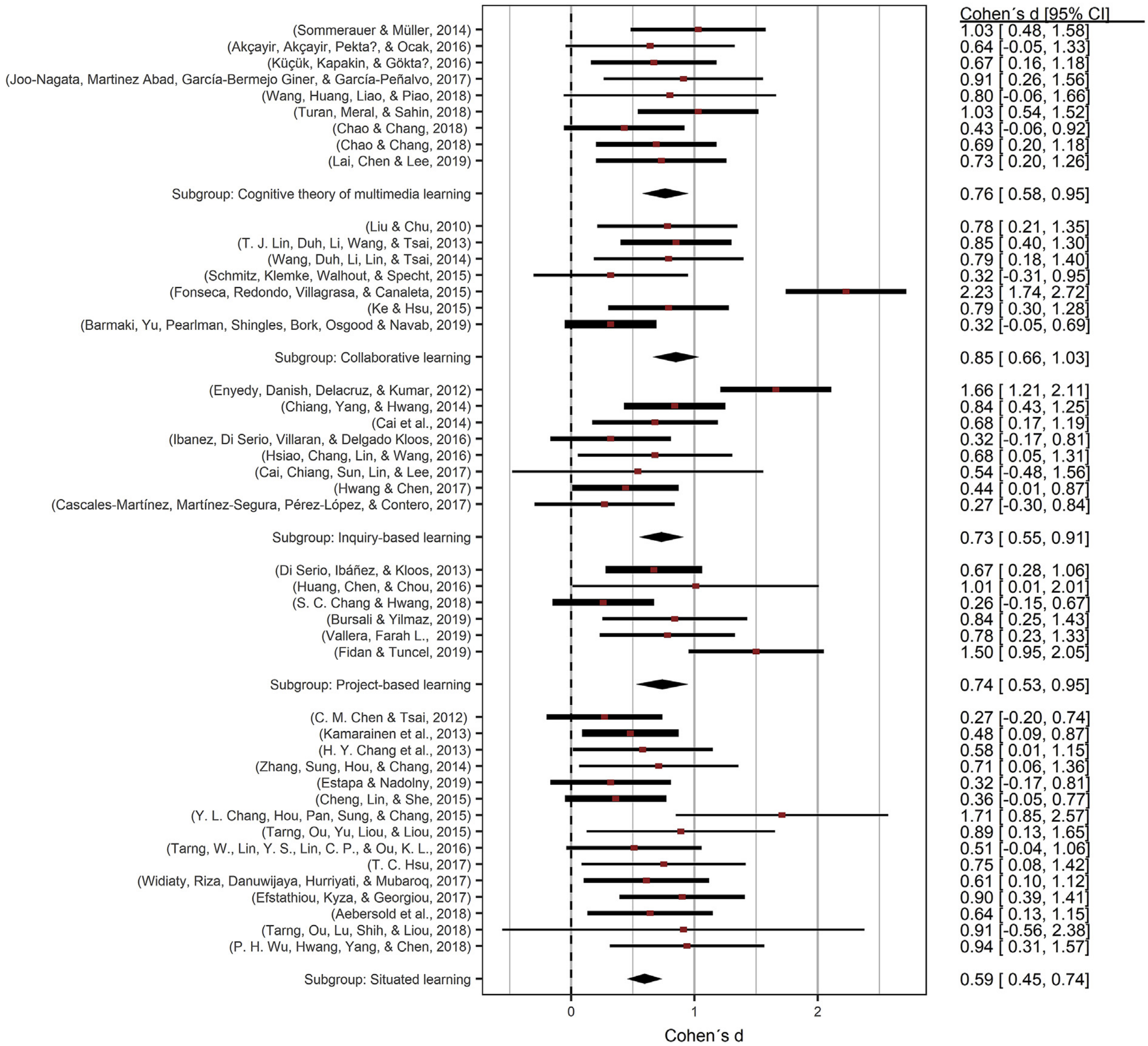

Fig. 3. Effect of AR according to the pedagogical approach.

outcomes.

5.2.3. Cross analysis

We performed a cross-analysis to identify the effect of the moderator variables depending on the field of education and the level of education in each study, using an ANOVA and a post-hoc Tukey test. We used the broad fields of education and the levels of education proposed by the International Standard Classification of Education (ISCED) (UNESCO, 2012). Fig. 6 shows the effect of the pedagogical approach, the learning environment, and the intervention duration depending on the field of education of each study.

According to Fig. 6, there are no significant differences in the students' learning outcomes in the fields of Arts and Humanities, Natural Sciences, and Health, depending on the learning approach, learning environment, or intervention duration. As for the field of Social Sciences, there are no differences depending on the learning approach and the intervention duration, but FS seems to present better results than IS. The field of Engineering presents statistically significant differences depending on the pedagogical approach and the intervention duration. Thus, SL pedagogical approach and interventions that lasted one week or more and less than one month, seem to benefit learning gains in this field of education. Finally, the small samples in the fields of ICT and Education do not permit to establish a reliable conclusion.

Subsequently, Fig. 7 shows the effect of the pedagogical approach, the learning environment, and the intervention duration according to the level of education of each study.

According to Fig. 7, there are no significant differences in the students' learning outcomes in the levels of Primary education, Lower secondary, Upper secondary, and Bachelor level depending on the learning approach, learning environment, or intervention

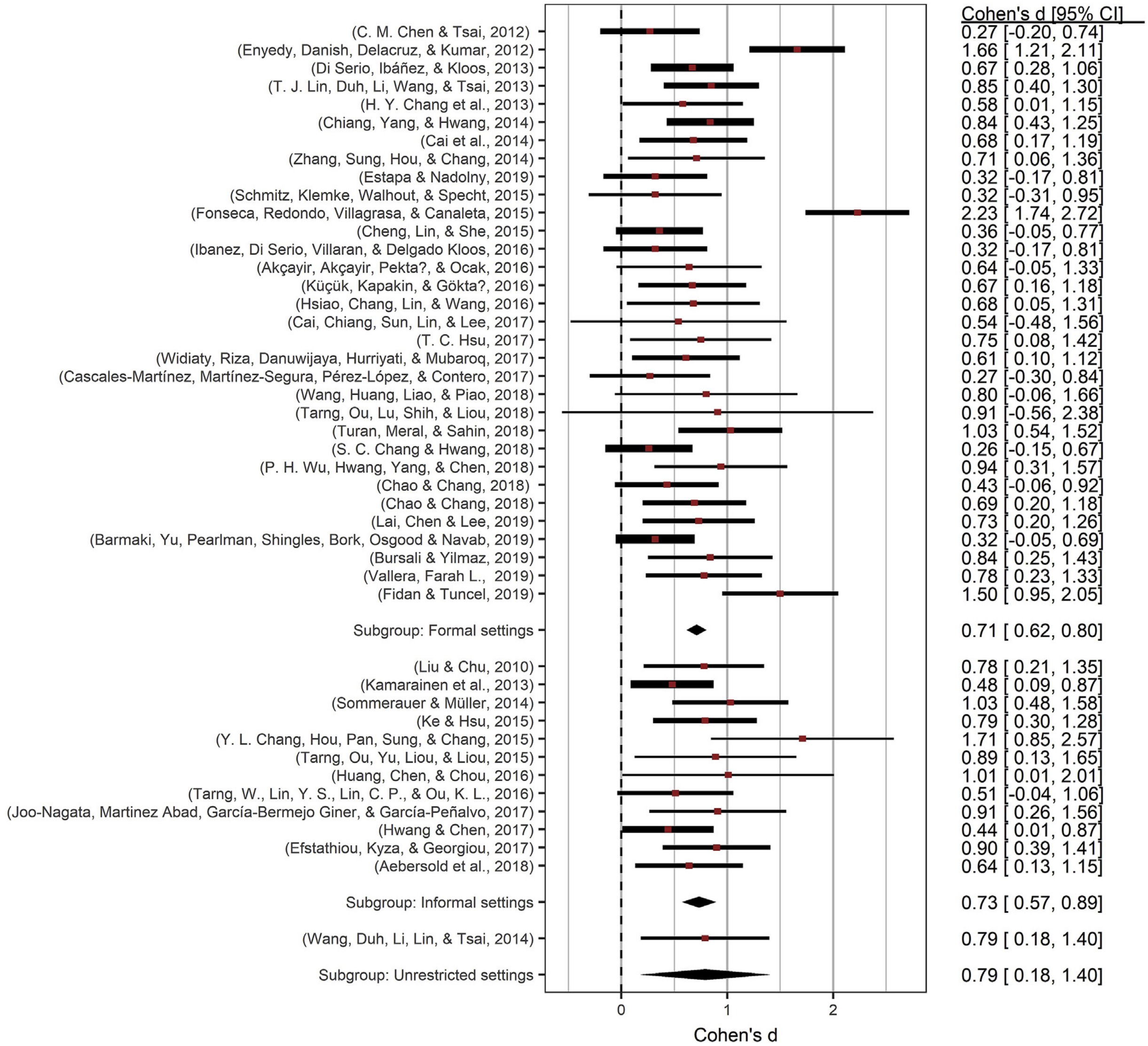

Fig. 4. Effect of AR according to the learning environment.

duration. Finally, the small sample in the level of Tertiary education does not permit to establish a reliable conclusion.

5.3. Publication bias

One of the challenges of meta-analyses studies is publication bias. It occurs when the results of an experiment influence the decision whether to publish or otherwise distribute it (Rosenthal, 1991). To evaluate the confidence of our results, we performed two different analyses: the fail-safe number and the trim and fill method. The fail-safe number indicates the number of missing studies with an ES of 0 that would have to be added to the study to reduce the total ES to insignificant. If this number is larger than $5k + 10$, where k is the original number of studies included in the meta-analysis, it can be assumed that the estimated ES of unpublished studies is unlikely to affect the overall ES. The fail-safe number for this meta-analysis was found to be 8913 following Rosenthal's procedure (Rosenthal, 1991). This value is larger than $5K + 10$, which suggests that the publication bias is unlikely to be a problem in the meta-analysis. Additionally, we applied Duval and Tweedie's trim and fill method to exhibit the calculated ES against the precision with which it is estimated (Duval & Tweedie, 2000). As shown in Fig. 8, 90% of the studies fit reasonably in the funnel without significant asymmetries around the found Cohen's *d* value, indicating that there is no evidence of publication bias. Likewise, the sunset funnel plot (Fig. 9) shows the median of power of all the studies, indicating that our metanalysis has the ability to detect significant differences in favor of AR with a probability of 75.6%. The sunset funnel plot also provides information about the statistical power of the studies to detect an effect of interest, using a two-sided Wald test. Results indicate that this meta-analysis has a probability of 82.3% to be replicated and obtain the same results.

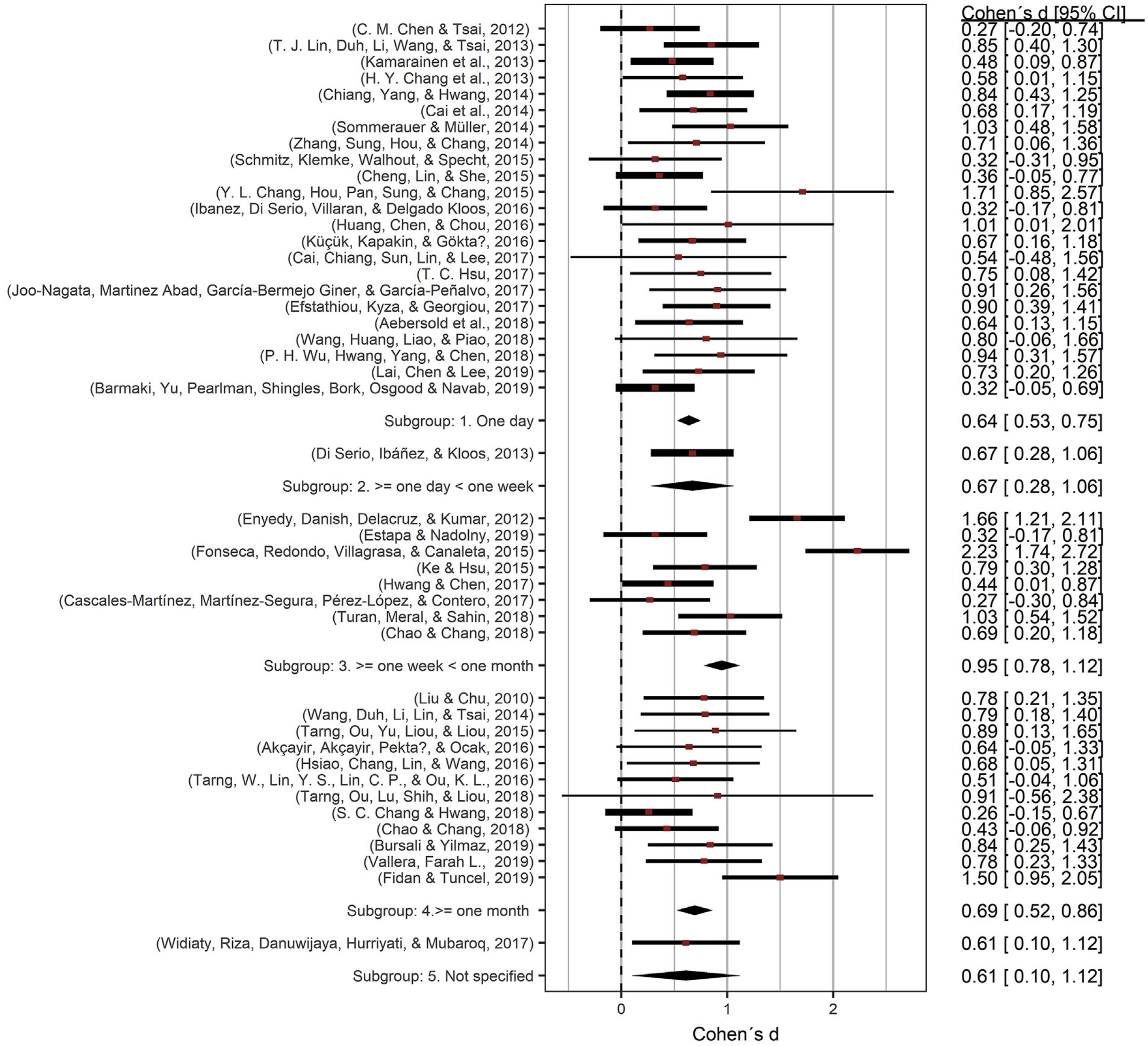

Fig. 5. Effect of AR according to the intervention duration.

6. Discussion

The main contribution of this study is the analysis of the influence of pedagogical approaches on the impact of AR applications on education. Although the focus of the research was not on calculating the overall ES of AR on education, it was necessary to evaluate the impact of the pedagogical approaches on students' learning outcomes. The overall ES was found to be $d = .72$, which indicates that AR has a medium impact on learning gains as stated in previous studies (Garzón & Acevedo, 2019; Ozdemir et al., 2018; Santos et al., 2014; Tekedere & Göker, 2016). However, this result is not the effect of AR alone, but the effect of the combination of different variables that influence AR interventions. Next, we describe the effect of factors such as the pedagogical approach, the learning environment, and the intervention duration, to establish how these characteristics of AR interventions moderate students' learning outcomes.

6.1. Pedagogical approaches

The results indicate that CL is the pedagogical approach that most benefits AR interventions. Following Cohen's classification, our results show that CL is the only pedagogical approach that has a large effect on students' learning outcomes. Some studies have found that AR may cause cognitive overload due to the amount of material and complexity of tasks students must perform (Akçayir & Akçayir, 2017; K.-H.; Cheng & Tsai, 2013; Dunleavy, Dede, & Mitchell, 2009; R.; Yilmaz & Goktas, 2017). To reduce this problem, it seems appropriate to use CL, which has been described as a useful approach to decrease the cognitive load. Moreover, it has been

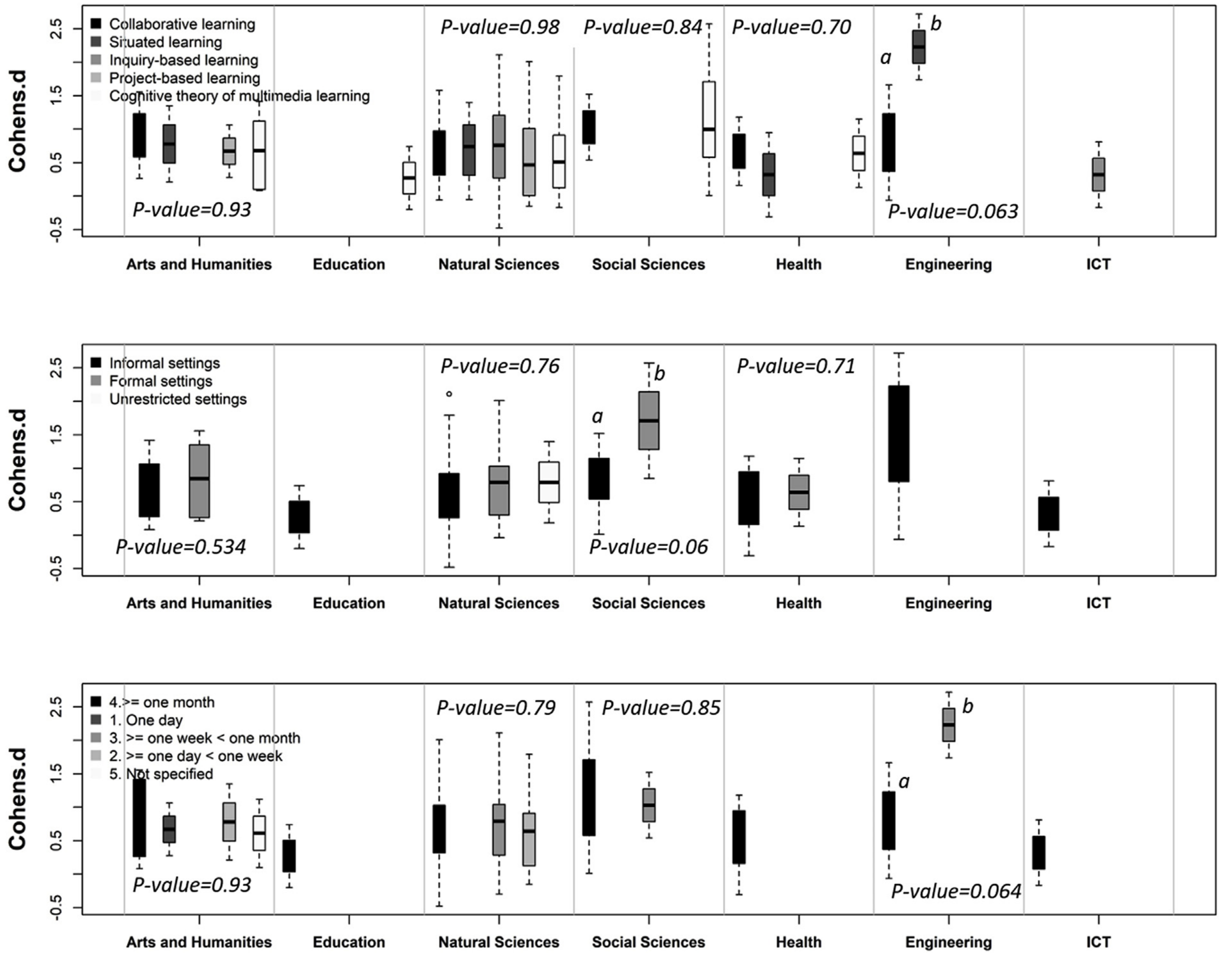

Fig. 6. Cross analysis of field of education with the moderating variables.

proven that technologies such as AR improve learning outcomes in collaborative environments (Turan et al., 2018), especially in science learning, which may explain the positive results in this meta-analysis.

The ES was found to be medium to high in the CTML, PBL, and IBL approaches. CTML is the most versatile approach since it has been used in AR interventions that involve each field of education and level of education proposed by the ISCED (UNESCO, 2012). This approach focuses on finding effective instructional methods instead of specific technologies (Mayer, 2017), which makes it a dynamic approach that will expand beyond the life cycle of any particular technology. Similarly, PBL is a versatile approach that can be successfully implemented in different scenarios. This approach has gained importance in recent years because it fosters in students values such as collaboration, motivation, and responsibility for their own learning, which will form the basis for the way they will work with others in their adult lives (Fidan & Tuncel, 2019). IBL has been exclusively used in AR interventions that involve the broad field of natural sciences. Inquiry activities are enhanced with AR because it enables the creation of highly realistic or virtual substitute for the real work that students can explore via their own investigation. Moreover, the success of IBL depends on a high motivation level of students (Hwang & Chen, 2017; Ucar & Trundle, 2011). Motivation has been described as one of the most relevant advantages of AR in education, which may explain the positive results of this approach in AR interventions.

Finally, the ES was found to be medium in SL approach. Although SL has the lowest ES, this is the most popular approach in AR interventions because AR applications can be situated in any educational environment. The ES was found to be a bit more positive in higher levels such as bachelor and tertiary education, compared to lower levels such as secondary and primary education. In this regard, Stein (1998) argues that adult students have a stronger theoretical background, which will facilitate the creation of the link between a specific scenario and what they already know.

6.2. Moderating analysis

6.2.1. Learning environments

The analysis shows that although there are no significant differences, the ES of AR interventions conducted in IS is slightly higher than the ES of AR interventions conducted in FS. Also, there is no tendency to use a specific learning scenario depending on the

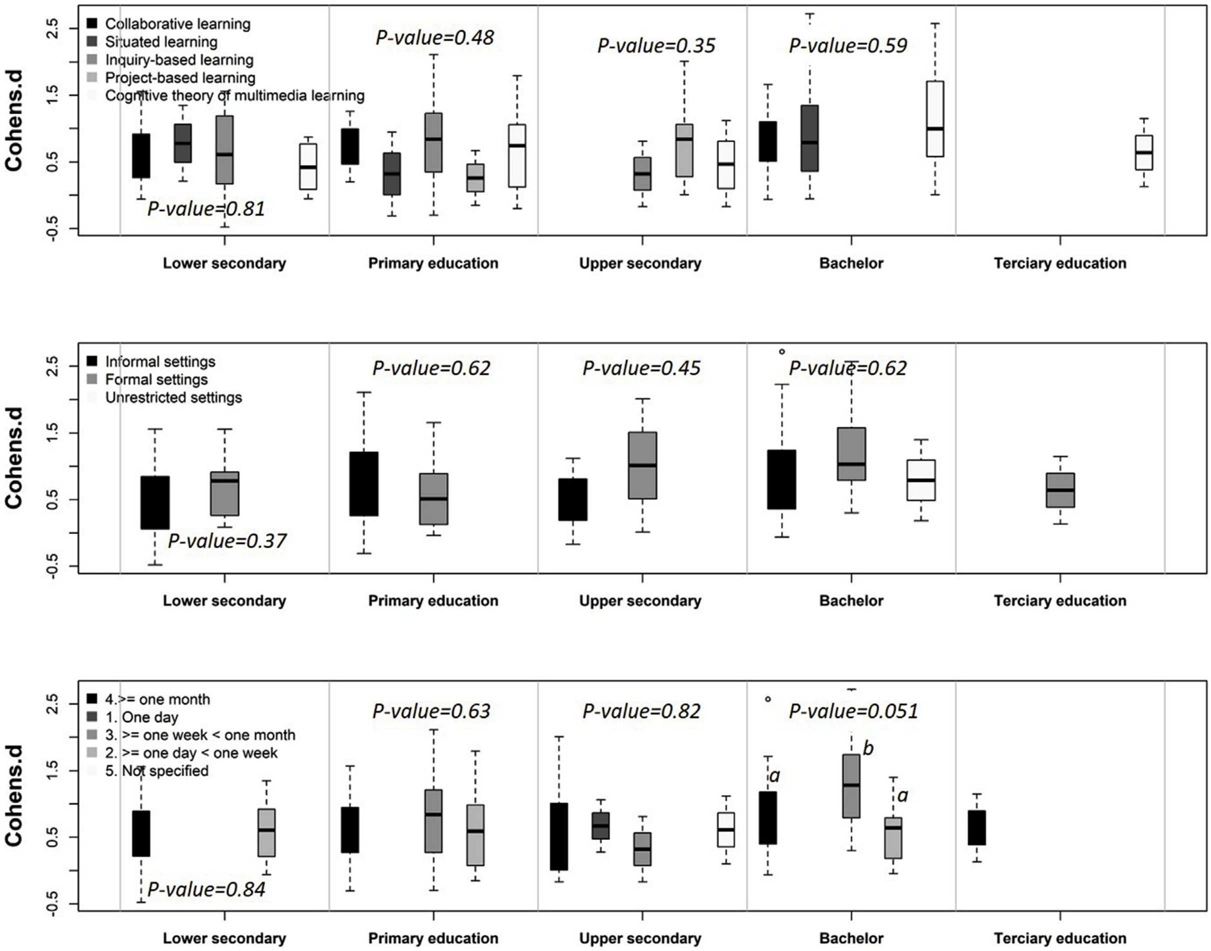

Fig. 7. Cross analysis of level of education with the moderating variables.

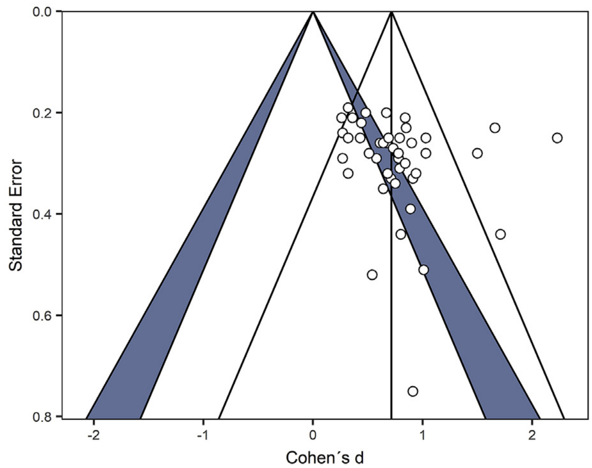

Fig. 8. Trim and fill method to estimate the possibility of publication bias.

pedagogical approach, the field of education, the level of education, or the intervention duration. According to Cohen's classification, both IS and FS have medium to high impact on education. The most popular pedagogical approach in IS is SL; however, the highest impact was obtained when using the PBL approach. The positive result of using the PBL approach in IS can be explained according to the fundamentals of PBL. These fundamentals suggest that it is important that students learn to solve problems in real-world contexts,

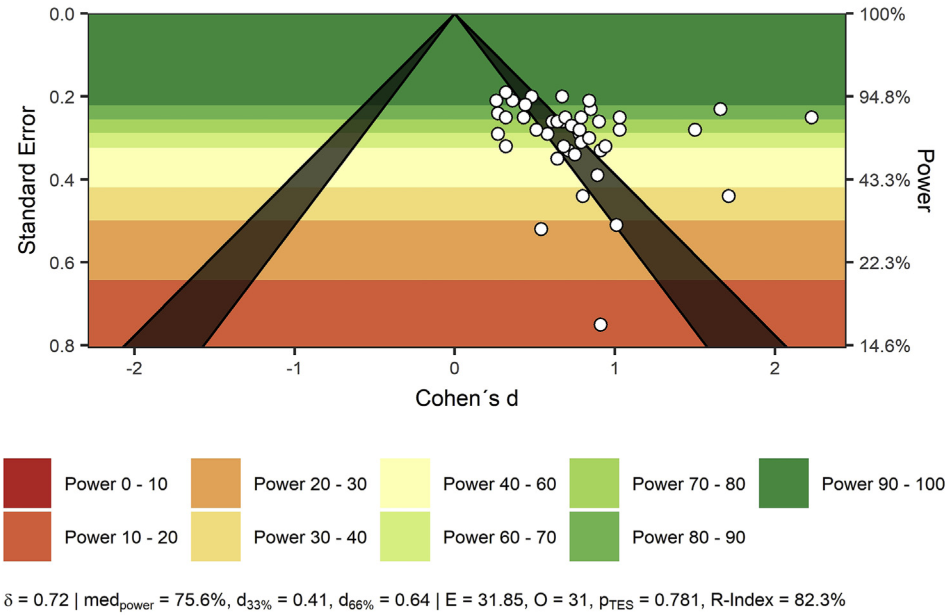

Fig. 9. Sunset (power-enhanced) funnel plot.

having the opportunity to witness the practitioners solving similar problems (Bell, 2010). In this sense, some authors argue that the greatest potential of AR is in IS due to its context-awareness and interactivity (Dede, 2009; Sommerauer & Müller, 2014).

On the other hand, although the most popular pedagogical approach in FS is CTML, the highest impact was obtained when using the CL approach. This approach has been proven to reduce the cognitive load of students, allowing them to focus specifically on the learning content they must learn. Some authors argue that some informal conditions may increase the cognitive load (Kirschner, 2002; Merriënboer & Sweller, 2010), and therefore, the use of formal environments seems to be appropriate in combination with the CL approach. Only one study was conducted in US and therefore, there is not enough information to determine the effect of this category.

6.2.2. Intervention duration

The study by Garzón et al. (2019) highlighted the need for longitudinal studies to discard the novelty effect of AR. Some studies have indicated that the impact of technological tools is more positive in brief duration interventions as artificial conditions can be created by researchers for a short period (Cheung & Slavin, 2013). In contrast, other studies indicate increased student performance scores over long periods of time because the continuous exposition to the pedagogical tools benefits the learning process (Chauhan, 2016).

Our results seem to contrast the previous findings because the highest ES was obtained when the interventions lasted between a week and a month. This is the only intervention duration category with a large effect on students' learning outcomes. Additionally, it is important to mention that CL was the most be effective approach within this category, with a very large effect according to Cohen's classification. Fundamentals of CL establish that particular forms of interaction among people trigger learning mechanisms. However, this interaction does not occur overnight but takes more time than other approaches to learning (Dillenbourg, 1999). Accordingly, we conclude that knowledge acquisition in CL takes time and effort to succeed, but when done properly, it provides invaluable learning experiences for students. One day interventions and one month or longer interventions showed a medium impact on education. Only one study had a duration between a day and a week, and therefore, there is not enough information to determine the effect of this category. Similarly, one study did not provide information on the duration of the intervention.

6.3. Implications for theory and practice

The results of this study confirm that an adequate combination of AR technology and specific pedagogical approaches enrich educational settings. From a theoretical perspective, the findings of this study may offer teachers and researchers a reference to understand what pedagogical approaches seem to better benefit learning processes. In addition to integrating the findings of empirical studies, this research also attempted to differentiate the results based on the learning environment and the intervention duration. The results indicate that, while SL is the most common pedagogical approach, CL shows the greatest impact on students' learning. Regarding the learning environment, FS is the most preferred environment for AR interventions. However, the use of a specific learning environment does not pose significant differences in the impact of AR on education. The most effective pedagogical approach in FS is the PBL approach, while CL obtained better results in IS. Regarding the intervention duration, there is a remarkable finding, as the best results were found in interventions that lasted between one week and four weeks.

From a practical perspective, the findings of this study offer insights on what characteristics of AR interventions seem to better benefit students' learning outcomes. This study not only indicates trends in the implementation of certain methods but also measures the impact of each method to inform what characteristics should be considered in future research. Given the apparent good results, it seems good practice to encourage teachers and researchers to promote collaborative activities when involving students in AR interventions. Similarly, the effectiveness of informal learning settings suggests that AR interventions should be conducted more frequently as part of informal activities, rather than limiting the use of AR to classrooms and laboratories. Results also indicate that AR interventions that lasted between one week and four weeks produced better results in students' outcomes. However, a specific intervention duration may not work for other interventions. A deeper analysis of the results indicates that IS was more effective when the intervention lasted one or more months, and in contrast, FS was more effective when the intervention lasted one day. Similarly, the cross-analysis indicates that the effect of the moderating variables on students' learning outcomes does not depend on the level of education or the field of education in AR interventions. However, the field of Social sciences seems to benefit most from the FS learning environment and the field of Engineering seems to benefit most from the SL pedagogical approach. Regarding the level of education, the cross-analysis shows no significant differences in any of the moderating variables. Therefore, teachers and researchers are encouraged to identify, according to their needs and possibilities, an appropriate combination of intervention characteristics to obtain the best of AR to enrich educational processes.

6.4. Limitations and future research

The results shown in this study are not definitive considering that the range of options of pedagogical approaches is significantly wider. These results apply only to the pedagogical approaches that have been identified in the empirical studies of our sample. Nonetheless, we encourage researchers to explore different pedagogical approaches that will potentially benefit AR interventions.

7. Conclusion

The main purpose of this meta-analysis was to identify how the pedagogical approaches affect the impact of AR on education. Based on the analysis of 46 quantitative empirical studies, we conclude that AR has a medium impact on students' learning gains. Nevertheless, this result must be interpreted prudently considering that the results in each study may vary depending on a wide range of factors. Pedagogical characteristics of the intervention such as the learning method, the learning environment, the intervention duration, and other variables that were not considered in this meta-analysis, may influence the results in each study.

The results of this study are consistent with the claim that minimal guidance during instruction is not enough. However, evidence from the literature shows that the unique characteristics of technologies such as AR, favor teaching and learning processes. In that sense, we consider reframing the question, "do media influence learning?" to (in our context) "how can we use AR technology to enrich teaching and learning processes considering the variations in each educational context?". In this study, we attempted to answer that question to provide insights to stakeholders on how they can plan AR interventions to get the best of this technology to improve teaching and learning processes.

CRediT authorship contribution statement

Juan Garzón: Investigation, Writing - original draft. **Kinshuk:** Writing - review & editing. **Silvia Baldiris:** Conceptualization. **Juan Pavón:** Formal analysis, Supervision.

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12. ARtour: Augmented Reality-Based Game to Promote Agritourism

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1.9 (Q2)	356	0.427 (Q2)	0.776

Summary:

Our fourth specific objective proposes a set of design principles to guide the development of AR educational applications. These principles were validated through the development of an AR-based educational resource that met some of the gaps identified in previous AR applications. We focused on a broad field of education that had not been considered in AR applications: *Agriculture, forestry, fisheries and veterinary*.

With that in mind, we designed ARtour, an inclusive augmented reality-based educational resource to promote agritourism. ARtour is a wise farmer who guide tourists thorough an adventure that immerse them in a journey of exploration. The learning scenario to promote agritourism is aquaponics, a sustainable agricultural strategy that combines aquaculture (raising fish) and hydroponics (the cultivation of plants without soil) to produce fish and plants together in a single integrated system. The resource was designed based on situated learning theory and presents two types of experiences: “Field experience” and “Home experience”. The field experience takes place in a specific natural environment outdoors and the home experience can be carried out inside a classroom or at home, using a personal computer. It is composed of four levels, each of which corresponds to a specific subtopic within aquaponics, namely aquaculture, hydroponics, recirculation system, and eco-education. The study postulates that the use of ARtour will enrich outdoor learning experiences and allow tourists to learn basic principles of agritourism in the context of aquaponics.

ARtour: Augmented Reality-Based Game to Promote Agritourism

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Abstract. Agritourism is an extension of ecotourism, which encourages visitors to experience agricultural life at firsthand. The growing interest in this industry worldwide poses new challenges to the environment. Traditional tourism models have somehow endangered local biodiversity and, consequently, it is necessary to promote new models that include education. Eco-education is commonly conducted through passive learning approaches within educational institutions, which often result in poor student performance in real life. Therefore, it is necessary to generate active methodologies to enrich learning experiences. Augmented Reality holds the power to add multiple benefits to the learning processes. Accordingly, this study introduces "ARtour". ARtour combines an Augmented Reality experience with on-site experiences to learn about agritourism while encourages tourists to maintain responsible environmental behavior. The project considers two outdoor learning scenarios: aquaponics and subsistence crops. We posit that ARtour will enhance outdoor learning experiences and will be a useful guide to promote agritourism.

Keywords: Agritourism · Augmented reality · Eco-education Ecotourism

1 Introduction

Agritourism is form of ecological tourism of growing interest around the world. It includes a wide variety of activities such as farm stays, bed-and-breakfast, pick-your-own produce, agricultural festivals, farm tours, and others [1]. Weaver and Fennell [2] provided a widely accepted definition of agritourism as rural enterprises which incorporates both a working farm environment and a commercial tourism component. This industry has experienced a rapid growth in the last two decades [3], posing new opportunities and challenges for natural and social environments. If properly planned and implemented, agritourism can generate positive impacts on nature and communities. Among other benefits of agritourism, we can find income generation, employment opportunities, a stronger economy, and environmental education. Some studies have

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found that farmers who participate in agritourism activities are likely to obtain higher income levels than farmers who do not undertake such activities [4–6].

However, like other forms of tourism, environmental degradation is a potential problem of agritourism, which highlights the need to promote sustainable tourism models [7–9]. These models aim to ensure the balance between economic development and nature conservation and must include eco-education as an important component [10].

Eco-education is present in educational programs around the world. However, it is often conducted through passive teaching methodologies within the classrooms and occasional field trips are reduced to a sightseeing. These strategies do not encourage students to develop interest for ecological education, which usually results on poor student performance in real life [11, 12]. Many studies have found that learning processes become more significant when students develop feelings on the subjects they are taught [13–15]. That is, for knowledge to be meaningful for students, they need to feel motivated and develop emotional attachment. Therefore, it is important to consider active teaching methodologies that enhance real environment experiences to support the learning processes.

Augmented Reality (AR) is an important technology that has been successfully implemented in many fields [16, 17]. This technology helps enrich education by transforming passive learning materials into interactive multimedia learning materials [18–21]. Since the integration of AR technologies into mobile devices [22], the development of AR applications to support learning has rapidly increased and has effectively taken root in educational settings [21, 23, 24]. Caudell and Mizell [25] introduced the term "Augmented Reality" to describe the group of technologies that allow users to augment the visual field through the use of heads-up display technologies. However, current AR systems involve not only the sense of sight but also all the other senses. In this way, Akçayir and Akçayir [23] proposed a wider definition of AR as a technology that overlays virtual objects into the real world.

The integration of AR systems into educational environments, provides multiple benefits that have been identified by different studies. These studies have concluded that learning gains and motivation are the two most reported advantages of AR systems for education [19, 21, 23]. Another important advantage reported by the studies, has to do with the fact that the integration of AR systems into mobile devices favors "mobile learning" [24]. Mobile learning allows learning processes to be carried out in outdoor learning environments, providing learners with different strategies to acquire the knowledge.

This paper presents an Augmented Reality-based game to promote agritourism named "ARtour". The project is in an early stage of development and includes the design, implementation and validation of the system through outdoor learning experiences at the final stage. ARtour is a wise farmer, who introduces basic concepts of agritourism and at the same time encourages tourists to maintain responsible environmental behavior. In addition, this research proposes to identify the impact of the ARtour system on the users learning effectiveness, addressing the following research questions (RQ):

RQ1: What is the effect of an augmented reality-based educational game on users learning gains in real-world observations?

RQ2: Are there statistically significant differences in the users' motivation according to the learning scenario they use?

RQ3: What is the degree of user satisfaction after using the ARtour application in outdoor learning scenarios?

The project considers two outdoor learning scenarios: (1) Aquaponics and, (2) Subsistence crops. To evaluate the effectiveness of the system, we propose two case studies (one per learning scenario). To identify the effect of an augmented reality-based educational game on users learning gains (RQ1), we propose to evaluate the Effect Size (ES) of ARtour on the learning effectiveness of the users. In this context, learning effectiveness is defined as the improvement in a user's learning between the beginning and the end of the intervention through the AR application. Likewise, "user" refers to the "tourist" who participates in the field trip. To evaluate users' motivation (RQ2) we propose the motivational measurement instrument Instructional Materials Motivation Survey (IMMS) [27]. Finally, to measure the degree of user satisfaction, we propose a satisfaction survey that uses a 7-point Likert scale.

2 Related Work

Many studies have found that the integration of AR systems into educational environments adds multiple benefits to teaching-learning processes. A literature review study conducted by Garzón et al. [21], analyzed 50 studies published between 2011 and 2017 (40 case studies and 10 literature review studies. This review analyzed the reported advantages and challenges of AR systems for education. Likewise, the study identified the most common target groups as well as the most common fields of education in the studies. The review found that the most reported advantages are learning gains and motivation and the most reported challenges is that AR systems are difficult for students to use. Regarding target group, the study found that most studies are focused on students from primary education, secondary education, or bachelor education. In contrast, there are some target groups such as vocational education students that have not been considered in the studies. As for fields of education, the study found that AR is most applied to teach subjects related to Natural Sciences or Mathematics. On the other hand, some fields of education such as Agriculture and Forestry have not been considered in the studies. Another important finding of the review is that only one study included aids for users with particular needs, which represents a step-back in terms of social inclusion. However, although Natural Sciences is the most common field of education in AR systems, most of these applications are related to physics, chemistry, anatomy, and biology. In contrast, applications related to eco-education are limited in number [12, 28–30], and none is related to agriculture or forestry.

3 ARtour

3.1 Concept of the Project

ARtour is a game based on AR technologies that promotes agritourism while encourages tourists to maintain responsible environmental behavior. By using ARtour, tourists will be the protagonists of an adventure that will immerse them in a journey of exploration. They will have the opportunity to learn and discover about the treasures that are hidden in Colombian landscapes. ARtour (Fig. 1), a wise farmer who represents the spirit of Colombian farmers, will guide this trip. He will provide users with the information and instructions to interact with the platform on which the experience is developed.

Fig. 1. ARtour, the wise spirit of Colombian farmers

The objective is to involve users in a story with the mission of learning about agritourism activities. They will be the protagonists of the mission and will assume an active role throughout the learning adventure. It is an immersive experience that seeks to impact users, so that they are motivated to take this experience to another level.

3.2 Description

When executing the application for the first time, the user is received by ARtour who presents himself as the guide of the experience and names the user "Explorer". ARtour is a wise farmer with the ability to communicate in multiple ways such as speech, images, texts and sounds. ARtour's guidance will allow the explorer to know beforehand the principles of agritourism and the rules that must be followed to be environmentally responsible.

The video game will involve the Explorer into a wonderful interactive audiovisual journey that stimulates his/her senses and mind. Unimaginable sounds, fantastic animals, and colorful flora are part of biodiversity that are presented in this amazing expedition. At the end of each stage of the trip, in addition to the experience and knowledge that has been collected, the Explorer becomes the creditor of a representative virtual piece. The Explorer accumulates virtual pieces as a reward which are added to a piggy bank. Each piece has a magical power and can be used to access other digital content to learn additional information about the treasures of Colombian agriculture.

4 Learning Scenarios

The ARtour project comprises two initial learning scenarios: (1) Aquaponics and (2) subsistence crops. Further projects will expand the experience, including other forms of agriculture.

4.1 Aquaponics

Aquaponics combines aquaculture (raising fish) and hydroponics (the cultivation of plants without soil) to produce fish and plants together in a single integrated system [31]. The implementation of these systems in Colombia increased over the last decade and became an important component of Colombian government's intention to increase food self-sufficiency of farmers.

It is estimated that the volume of production varies between 25–35 kg/month of fish and between 45–50 kg/1.5 month of vegetables for an aquaponic system of 16 m^2. This supposes a large extent of the monthly food requirement of a family of 4–6 people. Furthermore, surplus production volumes can be marketed to generate additional revenue.

ARtour gives the Explorers basic information about the main functions of an aquaponic system. The trip consists of four stages. The first stage explains basic information about aquaculture. The second stage explains basic information about hydroponic systems. The third stage explains how these two systems are integrated into a single system and, finally, the fourth stage gives important information about the rules of responsible behavior to apply when interacting with this type of system. When the Explorer finishes the experience, he/she can exchange the accumulated credit into new information. This information is related to the process of construction of aquaponic systems.

4.2 Subsistence Crops

Subsistence agriculture is a self-sufficiency farming system that farmers grow to use or eat themselves and their families, rather than to sell [32]. According to the Food and Agriculture Organization (FAO) of the United Nations, Colombia is one of the countries with the greatest potential for expanding land for agricultural use in the world. Accordingly, the Colombian government and the former guerrilla group of the Farc, presented a plan that seeks to replace 50000 hectares of illicit crops with subsistence crops. This initiative has to objectives: (1) to reduce the number of illicit crops in Colombia and (2) to secure food self-sufficiency of Colombian farmers.

ARtour gives the Explorers basic information about the main functions of a Subsistence crop. The trip consists of four stages. The first stage explains basic information about subsistence agriculture. The second stage explains what type of food can be grown in a subsistence crop according to the climatic conditions and the size of the crop. The third stage gives important information about the rules of responsible behavior to apply when interacting with this type of system. When the Explorer finishes the experience, he/she can exchange the accumulated credit into new information. This information is related to the process implementing urban subsistence crops.

5 Case Studies

We propose to conduct two case studies, one per learning scenario, each of which will be carried out in a locality of the province of Antioquia, Colombia. To assess the effectiveness of the system, we propose a quasi-experimental research structure that includes quantitative and qualitative methods.

5.1 Participants

Each case study will adopt vocational education students as a target group. Vocational education students refers to students who have finished secondary school but are not willing to enroll in a university [33]. These students have been labeled as promising research partners for validation and for demonstrating the possibilities of AR learning scenarios [34]. However, as many literature review studies have reported [20, 21, 23], these students have barely been taken into account as a target group in AR applications. The study by Garzón et al. [21], emphasizes the importance of the inclusion of these unexplored target groups to benefit such students from the affordances that AR systems adds to the learning processes.

Each case study will have an approximate number of 50 students and will be made up of experimental and control groups. Both groups will be trained by the same instructor to eliminate the confounding factors on the experimental results of different personalities, teaching styles, and teaching methods [35].

5.2 Experimental Instruments

The search includes as experimental instruments the pre-test, the post-test, the motivational measurement instrument IMMS, and the satisfaction survey. The pre-test aims to identify previous knowledge of users about agritourism. This test is taken by students from experimental and control groups. Users of both groups take the post-test at the end of the experience. This test aims to identify the knowledge acquired by users after having been trained by either of the two methodologies. The credibility of both the pre-test and the posttest, will be assessed using the Kuder-Richardson reliability formula.

To assess the impact of the learning approaches on the students' learning motivation, we propose the motivational measurement instrument IMMS. It includes 36 questions in 4 subscales, scored using a 5-point Likert scale. Each level ranges from "strongly disagree" (1) to "strongly agree" (5). The main components in the IMMS are attention, relevance, confidence, and satisfaction. Finally, the satisfaction survey aims to measure the degree of user satisfaction when using the ARtour application.

It consists of 10 statements that used a 7-point Likert scale. Each level ranges from "strongly disagree" (1) to "strongly agree" (7).

6 Results

As explained above, the project is at an early stage. Therefore, this section does not present obtained results but results that are expected after the validation of the project.

6.1 RQ1: What Is the Effect of an Augmented Reality-Based Educational Game on Users Learning Gains in Real-World Observations?

To guarantee equivalent prior knowledge of the students in the experimental and control groups, a t-test is proposed in terms of their pre-test grades. Next, to identify the outcomes of the students when using different learning methodologies, a t-test is proposed to compare the post-test grades between the two groups. Finally, to measure the effect of the ARtour System on the learning effectiveness of the users, we propose to calculate the ES based on Cohen's *d* ES using the following formula:

$$ES = \frac{\left(\bar{X}_{1\_post} - \bar{X}_{1_{pre}}\right) - \left(\bar{X}_{2\_post} - \bar{X}_{2\_pre}\right)}{SD_{post}} \quad (1)$$

Where, $\bar{X}_{1\_post}$ and $\bar{X}_{1\_pre}$ are the mean scores of the post-test and pre-test of the experimental group, respectively. $\bar{X}_{2\_post}$ and $\bar{X}_{2\_pre}$ are the mean scores of the post-test and pre-test of the control group, respectively. Finally, SD_{post} is the pooled standard deviation for the post-test:

$$SD_{post} = \sqrt{\frac{\left(n_{2\_post} - 1\right)S^2_{2\_post} + \left(n_{1\_post} - 1\right)S^2_{1\_post}}{\left(n_{2\_post} + n_{1\_post} - 2\right)}} \quad (2)$$

Where n_{2_post} and n_{1_post} are the sample sizes of the experimental and control groups, respectively. S_{2_post} and S_{1_post} are the standard deviations for the experimental and control groups respectively for the post-test.

6.2 RQ2: Are There Statistically Significant Differences in the Users' Motivation According to the Learning Scenario They Use?

To evaluate users' motivation (RQ2) we use the motivational measurement instrument Instructional Materials Motivation Survey (IMMS) [27]. This instrument measures learner motivation following the ARCS model and is particularly relevant to evaluate the impact of technology as a motivational factor in learning [36].

6.3 RQ3: What Is the Degree of User Satisfaction After Using the ARtour Application in Outdoor Learning Scenarios?

An additional test is proposed to be applied to users, once the educational experience is completed. It is a satisfaction survey (Table 1) validated and used in other investigations [37] and modified to be applied in this research.

Table 1. Satisfaction survey.

Question/affirmation
1. I am comfortable using the application
3. It is easy to navigate within the application
4. The information displayed in the application is accurate
5. The application has given me a positive impression about agritourism
6. The application has given me important information for my learning
7. The graphic design of the application is visually appealing
9. I was given enough information for the use of the application
10. I like the information that shows the application

The users are requested to rate the degree of agreement with each of the 10 statements based on a Likert type scale with 7 levels. Each level ranges from “strongly disagree” (1) to “strongly agree” (7). This instrument will allow us to know the perception of the users, their feelings and the degree of satisfaction with the use of the proposed system. In addition, to gain more qualitative feedback, we propose to conduct a short an informal interview to some of the users of the application.

7 Conclusion and Future Work

We posit that the use of ARtour will improve outdoor learning experiences and allow tourists to learn basic principles of agritourism. ARtour will motivate and facilitate the learning experience of tourists while having fun playing an AR game. ARtour intends to extend the concept of agritourism to a broader concept of Eco-agritourism, by showing tourists the importance of protecting and conserving of nature. In addition, ARtour encourages the tourists to build their own agricultural systems, if possible at their own spaces. Further research is pretended to be developed along with the ministry of tourism in Colombia. This research will focus on developing a wider set of options for tourist to visit and learn about agritourism activities.

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13. Augmented Reality-based application to foster sustainable agriculture in the context of aquaponics

Reference:

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Summary:

In this study, we present the development and validation of ARtour as a pedagogical tool to promote sustainable agriculture techniques in the context of aquaponics. The resource was designed using Unity 3D, Vuforia SDK, Inkscape, and the open-source 3D computer graphics software Blender, following the principles of instructional design. Subsequently, to validate the resource we designed a case study that involved 10 students to learn about aquaponics. Traditionally, the development of educational software follows the guidelines of IDM. These models propose a series of common rules to maximize the software creation process through five stages: analysis, design, development, implementation, and evaluation. Implementing instructional design helps create more engaging pedagogical tools that adapt to the specific needs of students and educators. To develop the proposed application, we used the ADDIE IDM. The main reason for this selection was that, unlike other models, ADDIE is a non-linear and flexible model where each stage interacts with each other.

We designed a case study to validate the effectiveness of the application. As mentioned, the application provides two types of experiences: field experience and home experience. The validation process was carried out in the home experience considering that the field experience requires displacement to an aquaponic system, which implies a greater investment in time and money. Results indicate that the students had a positive perception of the resource, which suggests that this is appropriate to foster sustainable agricultural strategies in the context of aquaponics.

Augmented Reality-based application to foster sustainable agriculture in the context of aquaponics

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Abstract— **Population growth implies the need to produce more food. This increases pressure on the planet's resources, which drives climate change and challenges environmental sustainability. Hence, it is important to promote sustainable agriculture strategies that contribute to global food and nutrition security while protecting natural resources. These strategies should be guided from an educational perspective that motivates people to develop positive bonds with nature. In this regard, augmented reality has emerged as a technology with the potential to improve environmental education programs. This paper presents the development and evaluation of an augmented reality-based educational application, whose purpose is to foster sustainable agriculture in the context of aquaponics. The application was developed using Unity and Vuforia following the principles of instructional design. To evaluate the effectiveness of the application, we designed a pilot study with 10 volunteers. The results indicate that the application has the potential to motivate users to learn, which suggests that it is appropriate to foster sustainable agriculture strategies in the context of aquaponics.**

Keywords-aquaponics; augmented reality; environmental education; sustainable agriculture

I. INTRODUCTION

One of the main challenges for the environment is a growing world population. According to the Food and Agricultural Organization of the United Nations (FAO), by 2050 there will be a 30 percent increase in the world's population. This implies the need to produce more food, increasing the pressure on the planet's resources --water, forest, land, and earth's atmosphere-- contributing to climate change and challenging environmental sustainability [1].

FAO states that transformative change in agricultural and food systems are required worldwide, in order to guarantee global food security at large. FAO adds that, although much progress has been made in recent years, it is imperative to foster new and improved sustainable agriculture strategies to reduce the impact of food production on the environment.

In this sense, as an alternative to produce vegetables, fruits, and protein in locations where soil-based agriculture is difficult, FAO promotes the implementation of aquaponics, a technique that has its place within the context of sustainable agriculture. Aquaponics is an emerging agricultural technology that combines aquaculture with hydroponics in a symbiotic system. Nutrient-rich aquaculture water is recirculated through hydroponic growing beds. All the nutrients required by the plants are supplied through the fish wastes, eliminating the need for fertilizer. Likewise, the plants clean the water for the fish, eliminating the need for water exchanges. An aquaponic system can be located inside a house or in very small spaces, thus providing a simple, cost-effective, and sustainable way of producing plants and fish.

The promotion of small-scale aquaponic units has been undertaken from various educational institutions and community-based organizations. This promotion is carried out in the context of environmental education programs as a vehicle to bridge the gap between population and sustainable agriculture techniques [2]. However, as identified by different studies, the success of environmental education programs depends largely on students' motivation rather than on their knowledge [3].

As an effective way to stimulate motivation, Augmented Reality (AR) has been implemented in different educational scenarios. It has been defined as the technology that allows users to see a supplemented reality through superimposed virtual objects over the real world [4]. The concept of AR is related to how technology can help us enrich our perception of reality by adding virtual information (in the form of image, sound, video, among others) to the physical and tangible reality that surrounds us. According to Santos et al. [5], this technology increases human sensory perception (visual, auditory, olfactory, etc.) with auxiliary information that can potentially improve results when performing a task or experience. Although AR has not been implemented to teach subjects related to agriculture [6], it has been successfully implemented in environmental educational programs as it helps students in their learning process and to develop positive bonds with nature [7].

With the above background, this paper presents the development and evaluation of an AR-based educational application, whose purpose is to foster sustainable agriculture in the context of aquaponics. First, we describe general aspects of the development process. Then we present the main results of a pilot study to evaluate the application and, finally, we discuss the results and offer some conclusions to be considered in future research.

II. APPLICATION DEVELOPMENT

Traditionally, the development of educational software follows the guidelines of instructional design models. These models propose a series of common rules to maximize the software creation process through five stages: analysis, design, development, implementation, and evaluation.

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Instructional design is considered to be the gap between effective pedagogical applications and average applications that are designed without explicit learning purposes [8]. To develop the application, we used the ADDIE instructional design model, as, unlike other models, this is a nonlinear model where each stage interacts with each other [9]. Next, we described the work done at each stage.

A. Analysis

The main purpose of this stage is gaining understanding of the target audience and the instructional goals. Although the application can be reused in different educational contexts, we defined vocational education students as the main target audience because of their potential to develop sustainable agricultural strategies as established by FAO [2]. Additionally, we selected the Android platform as this is the most widely used operating system worldwide.

B. Design

This phase includes the definition of the learning goals, the structure of the educational resource, the thematic contents, and the assessment instruments. According to the purpose of the study, the learning goal of the application is to serve as a pedagogical tool to teach aquaponics. We defined four levels to teach the fundamentals of aquaponics: 1) hydroponics, 2) aquaculture, 3) recirculating system, and 4) environmental education. The thematic content at each level is presented in the form of videos, texts, and graphics. In addition, the application provides a section of games in which users can practice what they have learned and, finally, an evaluation section to validate the efficacy of the learning process.

C. Development

The purpose of this stage is to develop the educational material for the application. To structure and present the contents, we chose the Unity cross-platform as it is considered to be the most cost-effective, flexible, and sustainable engine for developing AR applications [10].

The main character of the application was modeled using Blender and then added to Unity as an asset. In this software, comparative tools are property, which makes Blender suitable for the creation of educational content [11].

All the landscapes shown in the scenes were created using the free and open-source vector graphics editor Inkscape. This graphics editor provides a clear and user-friendly interface, which translates into a low learning curve [12].

Finally, to superimpose the virtual elements into the real environment we used Vuforia, the most popular software development kit (SDK) for developing AR applications [13]. Vuforia allows developers to position virtual objects to represent the academic content in relation to real-world objects when they are focused by the camera of a device.

D. Implementation

After finalizing the software development, the implementation of the application was held in the context of a pilot study that will be described in section IV. The purpose of the case study was to evaluate the effectiveness of the application as a pedagogical tool to teach aquaponics.

E. Evaluation

The evaluation of the application was held throughout the development process, namely during phases, between phases and after implementation. The evaluation during and between each phase is called formative evaluation and its purpose was to improve the application before the final implementation. On the other hand, the summative evaluation was carried out after the implementation in the context of a pilot study that will be described in section IV.

III. Application Description

The application provides two learning experiences: home experience and field experience. After selecting the learning experience, users must select a specific level. Each level of the application (hydroponics, aquaculture, recirculating system, and environmental education) matches a fixed station of the aquaponics system: the fish tank (aquaculture), the hydroponic system (hydroponics), the recirculating system (recirculating system), and the filtration system (environmental education). Each station includes four numbered trigger images located in different parts of the station. When users focus the camera of their mobile devices on each of these trigger images, it is displayed virtual information related to specific themes of the respective level, such as definition, importance, varieties, and functioning (see Fig. 1). Additionally, each level provides three extra activities (Learn+, Games, Evaluation), which will reinforce the knowledge acquired by users. When users explore the four levels, they are invited to access a final evaluation to validate what they have learned.

We provide a link to download the application for free. Additionally, we provide access to all trigger images (markers) used to activate the virtual information at each level and offer instructions on how to implement the field experience. In case an educator wants to conduct a case study to reproduce our experience, he/she can download and print all the markers and locate them in specific places of the aquaponic system.

Figure 1. Augmented scene explaining the definition of hydroponics.

IV. Pilot Study

We designed a pilot study to evaluate the application. The study was carried out in the home experience and involved 10 vocational education students who volunteered with the sole purpose of acquiring knowledge.

All the students were gathered in a classroom adapted with 10 workstations. The students received basic information about the study and then one of the researchers spent 15 minutes demonstrating how to use the educational application. Subsequently, each student sat at a specific station and explored the application for two hours.

After completing the exploration, the students received an adapted version of the Learning Object Review Instrument (LORI) to evaluate their perception of the application. LORI uses a Likert-style five-point response scale, with the items ranging from low (1) to high (5). Although LORI is intended to evaluate learning objects, it also supports the evaluation of multimedia learning resources [14].

V. Results

Table I summarizes the values given by the students regarding their opinion of the educational application as a pedagogical tool.

TABLE I. LORI Evaluation

Item	Value (1-5)
Content quality	4.60
Learning goal alignment	4.60
Feedback and adaptation	4.30
Motivation	4.70
Presentation design	4.70
Interaction usability	4.50
Accessibility	4.10
Reusability	4.70
Standards compliance	4.50
Total	4.52

Results indicate that the students gave a “High” rating to the application according to the LORI scale. The most positive items were motivation, presentation design, and reusability and the lowest score was obtained by accessibility.

VI. Discussion and Conclusion

The results indicate a positive perception of the students. Motivation, presentation design, and reusability were the items with the highest scores. These results are very relevant as motivation is considered a key aspect to guarantee the success of environmental education programs [3]. Presentation design highlights the quality of the visual and auditory information used for enhancing learning through the augmented scenes and contributes to students’ motivation to use the application. Similarly, reusability indicates the possibility of reusing this application in different contexts to expand the promotion of sustainable agriculture. In contrast, the lowest score was obtained by the item of accessibility. Although it is not a bad assessment, future versions of the application must consider reexamining its accessibility in order to extend its benefits to a larger population. Based on the results through the LORI, we conclude that this educational application has the potential to be used as a pedagogical tool to promote sustainable agriculture. Additionally, the learning effectiveness of the application has been demonstrated in a parallel study [15].

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14. Promoting Eco-Agritourism Using an Augmented Reality-based Educational resource

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Summary:

Agritourism is a type of ecological tourism that combines agricultural activities with tourism. There is a growing interest in this industry worldwide, which poses opportunities and challenges for social and natural environments. In this study, we present the validation of ARtour as a pedagogical tool to promote eco-agritourism. The educational content is focused on a scenario that is gaining popularity in agritourism: "aquaponics". Aquaponics is a food production technique, in which aquaculture and hydroponics are combined in a single integrated system to produce animal and vegetable proteins.

The application presents four levels which correspond to subtopics of aquaponics: 1) Aquaculture, 2) Hydroponics, 3) Aquaponic system, and 4) Eco-education. Each level matches a fixed station in a real aquaponic system: the fish Tank (Aquaculture), the hydroponic system (Hydroponics), the recirculation system (Aquaponic system), and the filtration system (Eco-education). Each station contains four numbered trigger images, each of which presents information related to a specific issue (definition, importance, varieties, functioning, among others). The learning contents are displayed when the user focuses the camera of the mobile device on the target images located in different parts of each station.

To analyze the effect of the educational resource on users' learning outcomes, we conducted a case study in the context of a field trip to a greenhouse aquaponic system. The results show that the resource has a medium effect size on learning gains and a large effect on knowledge retention. Likewise, the data indicates that the resource increased users' motivation to learn and practice responsible agritourism.