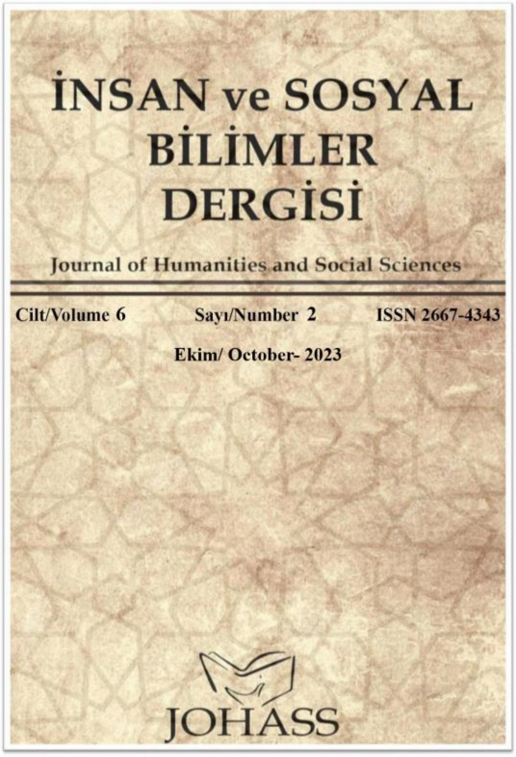
JOURNAL OF HUMAN AND SOCIAL SCIENCES (JOHASS)



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The Impact of Virtual Museum on Learning Achievement: A Meta-Synthesis Study*,**

** This study was presented as an oral presentation at the 10. International Eurasian Educational Research Congress (EJER) in Ankara on June 8-11, 2023.*
***This research was conducted as part of the preliminary field study of the project under the Scientific and Technological Research Council of Turkey (STRCT; TÜBİTAK) 3005 Innovative Solutions Research Projects Support Program in Social and Humanities Sciences.*

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Article Type: Research Article
Received: 4.10.2023
Revision received: 18.10.2023
Accepted: 26.10.2023
Published online: 27.10.2023

Citation: Mercan, G., Varol Selçuk, Z., & Özer Keskin M. (2023). The impact of virtual museum on learning achievement: A meta-synthesis study. *Journal of Human and Social Sciences,6*(1), 520-544.

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Abstract

This meta-synthesis study aims to explore the impact of virtual museum on learning achievement. With the advancements in technology, virtual museum and augmented reality museum applications have gained popularity in the field of education and museum studies. However, there is a need to examine their effectiveness in enhancing learning outcomes. This research reviews examines 17 studies to evaluate their effects on learning achievement. The findings reveal that virtual reality (VR) and augmented reality (AR) are frequently used in science, art, and history museums to support the acquisition of conceptual knowledge. These technologies are commonly employed for purposes such as integrating additional materials with physical exhibits, animating complex events or concepts, and simulating virtual exhibitions and story scenarios. However, the study also highlights some challenges and limitations of these applications. Technical issues, such as hardware requirements and connectivity problems, can hinder the effectiveness of the learning experience. Additionally, the availability of high-quality content and the need for instructional guidance are important factors to consider for successful implementation. Overall, this meta-synthesis study suggests that virtual museum and augmented reality museum applications have a positive influence on learning achievement. It emphasizes the potential of these technologies in enhancing the educational experience and recommends further research in this area to explore their long-term effects and address the identified challenges.

Keywords: Virtual museum, augmented realit, learning achievement, meta-synthesis, educational technology

Research Article

Received: 4.10.2023
*Revision received:*18.10.2023
Accepted: 26.10.2023
Published online: 27.10.2023

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Introduction

The International Council of Museums (ICOM) defines museums as public entities dedicated to the procurement, preservation, investigation, dissemination, and display of both material and immaterial aspects of human civilization and its surroundings (ICOM, 2007). They serve as platforms showcasing a wide array of objects, exhibitions, and programs that correspond to various disciplines including but not limited to science, history, archaeology, and art. Visitors of museums partake in educational experiences that enable them to comprehend the significance of historical artefacts, gather insights about science, history, and art, and acknowledge diverse cultures. Moreover, it is well documented that museum learning can spark interest and foster cognitive capabilities. Nevertheless, contemporary museums are grappling with a dwindling engagement and a drop in the number of young visitors. Thus, the crafting of captivating educational experiences is crucial to revive and maintain interest (Crowley et al., 2014; Hassan & Ramkissoon, 2016; Guzin et al., 2017).

Literature regarding museum learning often spotlights the role of technology within these institutions. As illustrated by Wang et al. (2017), location-based learning activities within museums, conducted using mobile devices, were assessed based on the usefulness of the system and activity, as well as the enjoyment derived from the activity. The study established that location-based systems, used alongside mobile devices, encouraged collaboration within student groups. The analysis by Lin et al. (2021) delved into the trends in museum-based mobile learning research, tackling subjects such as research methodologies, learning fields, location-based technologies, learning tactics, and research subjects. Furthermore, Xu et al. (2021) carried out a meta-analysis that evaluated 42 experimental or semi-experimental studies from the period between 2011 and 2021, and concluded that technological applications have a significant, and often substantial, impact on museum learning. In light of recent developments, virtual reality (VR) and augmented reality (AR) technologies are being progressively harnessed to devise impactful activities for learners.

Numerous empirical studies have investigated the application of AR and VR in the scope of museum learning, spanning various fields like science, art, archaeology, medicine, and military. Oh et al. (2018) created a multi-user simulation named ARfract employing optical see-through AR glasses, projection-based AR, and gesture technology. This innovative simulation empowers visitors to delve into intricate notions such as light refraction by leveraging the capabilities of optical glasses and projection-based AR. In a different study, Yoon et al. (2017) integrated an AR device within a science museum to aid students in gaining a more profound understanding of fluid dynamics, a complex subject linked to the Bernoulli principle. Additionally, AR and VR technologies are employed extensively across an array of museums, such as art, history, and archaeology museums, to enrich or simulate art pieces and artifacts. For instance, Chang et al. (2014) presented paintings through a mobile AR guide system in a highly interactive manner, which resulted in elevated interest among university students. Moreover, AR has been utilized within medical museums to showcase virtual labels, images, and natural interfaces that can enable students to gain a more in-depth understanding of medical specimens.

Learning outcomes derived from AR/VR-assisted museum learning, as evaluated in the pertinent literature, show variability and often encompass aspects such as knowledge attainment, thought processes, and individual perceptions. For instance, Yoon et al. (2017) found that when granted a brief review period within a science museum, students who used AR demonstrated considerably higher knowledge acquisition compared to those who did not. It has been reported by some studies that AR/VR-assisted museum learning amplifies higher-order cognitive abilities, such as creativity, inquiry, and critical thinking (Guazzaroni, 2013; Hsiao et al., 2016; Poce et al., 2019; Hammady et al., 2020). Other studies have also scrutinized learners' motivation and emotional responses. Dieck et al. (2018) and Puig et al. (2020) found that these technologies amplify visitor satisfaction and pleasure, and wearable devices contribute towards personalizing the learning experience. Additionally, Nechita and Rezeanu (2019) reported that a multisensory AR-assisted museum environment, which provides a firsthand experience of historical events, can foster empathetic skills. However, some studies have also identified negative implications of AR/VR-assisted museum learning. For instance, Savela et al. (2020) determined that AR games within science centers did not enhance learning performance or social interaction compared to traditional learning methods employing pen and paper. Learners have also reported feelings of nausea and vertigo with VR devices, and some gadgets, such as headsets, have led to physical discomfort for visitors (Oh et al., 2018; Rhee, 2019; Sugiura et al., 2019). Consequently, the degree and specific advantages of AR and VR applications within museum learning remain largely undefined, and additional research is warranted.

In recent years, AR and VR have become a key area of interest in educational research, particularly within formal educational contexts. Akçayır and Akçayır (2017) provided a comprehensive review of AR applications within primary and secondary education, exploring the benefits and challenges of AR and asserting its potential to support learning and teaching. Bacca et al. (2014) carried out a review of AR's application within educational settings and determined that AR is predominantly used within science, humanities, and art education. Radianti et al. (2020) conducted a review that examined VR applications within university settings, focusing on learning content, design elements, and learning theories. Saltan and Arslan (2017) offered a holistic overview of the evolution of AR research on pedagogical and educational outcomes, presenting evidence of improved academic performance and perceptions. Goff et al. (2018) examined AR within exhibition-based informal science education settings and reported the STEM-focused topics covered by AR applications, the array of devices used, and the positive learning outcomes.

The aforementioned reviews synthesize the trends, benefits, and challenges of employing AR and/or VR within educational settings, primarily focusing on formal contexts. However, a meta-analytic review of experimental studies on the application of AR/VR within the context of museum learning is yet to be conducted. Specifically, it remains unclear as to which contexts AR and VR technologies are deployed within museum learning and how learning activities involving AR and VR are devised (i.e., design elements). Moreover, while some studies report positive effects of AR/VR-assisted museum learning, others report negative effects.

The objective of this study is to offer a comprehensive meta-analytic review of AR/VR-assisted museum learning. Firstly, educational researchers and museum professionals might be interested in the information on the contexts in which AR and/or VR are used, the learning domains, and the learning content. Secondly, it is crucial to gain a more profound understanding of the opportunities offered by AR and VR and their associated design elements. Thirdly, ascertaining the overall effects of AR and VR on museum learning is of paramount importance. Therefore, the research questions are as follows:

1. In which contexts are AR and VR technologies deployed within museum learning?
2. What design elements are incorporated alongside AR and VR technologies within museum learning?
3. What are the effects of AR and VR technologies on museum learning?

This study holds significant importance for several reasons. First and foremost, it addresses the growing interest in the use of AR and VR technologies in the field of museum learning. While there is an increasing number of empirical studies exploring the application of AR and VR in various educational contexts, there is a lack of comprehensive meta-analytic reviews specifically focusing on their use in museum learning. This study aims to bridge this gap by synthesizing existing research and providing a comprehensive understanding of the application and effects of AR and VR in the context of museums. Secondly, understanding how AR and VR technologies can be effectively utilized in museum learning is crucial for enhancing the educational experience for visitors, particularly in the face of declining interest and decreasing visitor numbers among the younger generation. By designing engaging and immersive learning experiences, museums can attract and engage a wider audience, foster a deeper understanding and appreciation of cultural heritage, and promote lifelong learning.

Moreover, this study addresses the need for a deeper exploration of the design elements and contexts in which AR and VR technologies are applied in museum learning. By examining the different approaches and techniques employed in previous studies, researchers, museum professionals, and educators can gain insights into effective strategies for incorporating AR and VR technologies into museum environments. Furthermore, the findings of this study can contribute to the ongoing discourse on the effectiveness of AR and VR technologies in enhancing learning outcomes. By synthesizing the existing research on the effects of AR and VR in museum learning, this study can provide a clearer understanding of the impact of these technologies on knowledge acquisition, thinking skills, motivation, and other learning outcomes. This knowledge can inform future research, guide the development of best practices, and support evidence-based decision-making in the integration of AR and VR technologies in museum learning environments. In summary, this study's significance lies in its contribution to the field of museum learning by providing a comprehensive meta-analytic review of the application and effects of AR and VR technologies. The findings can inform educational researchers, museum professionals, and educators in their efforts to create engaging and impactful learning experiences, thereby promoting the preservation, communication, and appreciation of cultural heritage in museum settings.

Method

Model

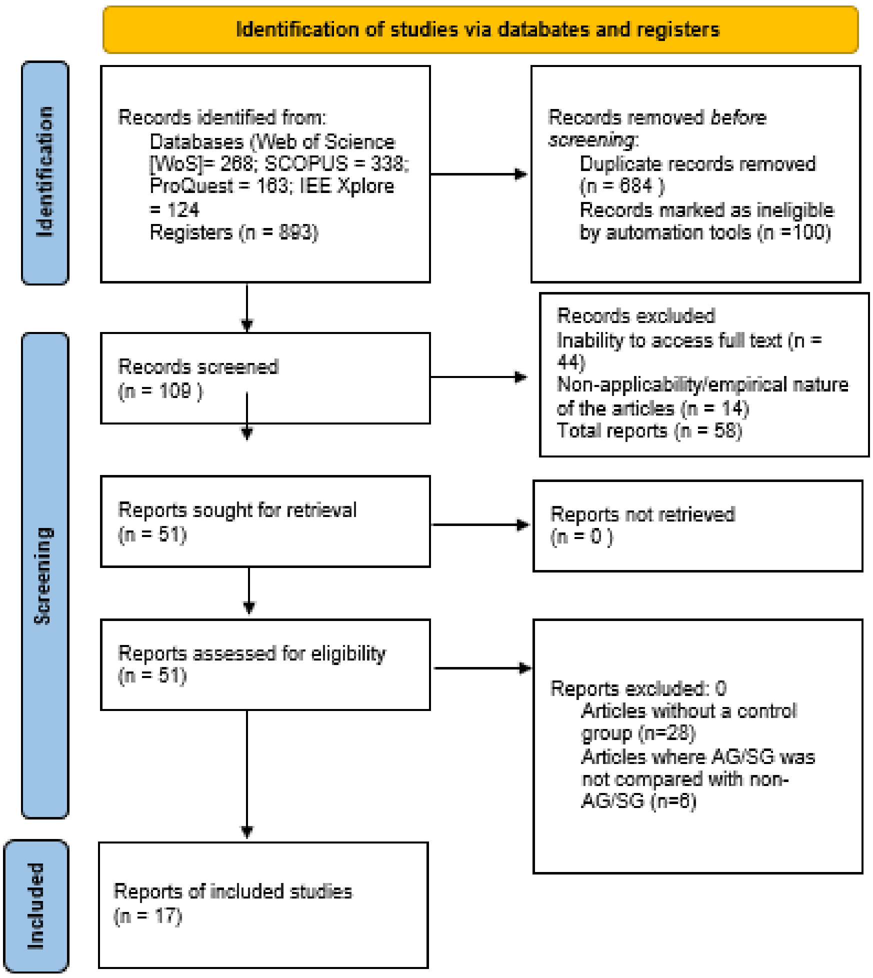
The present study utilizes a meta-synthesis approach to examine the impact of virtual museum and augmented reality museum applications on learning achievement in the context of museum learning. Meta-synthesis is a systematic and rigorous method for integrating findings from multiple empirical studies to generate new insights and develop a comprehensive understanding of a specific research topic (Noblit & Hare, 1988). In this study, a meta-synthesis of the existing literature was conducted to identify relevant articles on the topic.

Inclusion and Exclusion Criteria

The literature search was performed in various academic databases, including Web of Science (WOS), Scopus, IEEE Xplore, and ProQuest, using relevant keywords such as "virtual museum," "augmented reality," "virtual reality", "3D", "AR", "VR", "museum learning," and "learning achievement". The final search was conducted on April 30, 2023, without any limitations on the start date (Figure 1).

Figure 1

PRISMA (2020) Flow Diagram



As seen in Figure 1, a total of 893 studies were identified with the specified keywords/keyword groups from Web of Science (WoS) (n=268), SCOPUS (n=338), ProQuest (n=163), and IEE Xplore (n=124). The identified articles were transferred to an Excel file, and duplicate articles were removed. After removing 684 duplicate articles and 100 records marked as ineligible by automation tools, 109 articles remained for title and abstract screening. The titles and abstracts of these 109 articles were read by the researchers. After reading the titles and abstracts, 44 articles were excluded due to inability to access full text, and 14 articles were excluded due to non-applicability/empirical nature of the articles, leaving only the studies that the authors explicitly mentioned using relevant keywords in their titles and abstracts. This resulted in a total of 51 records remaining for full-text screening. After reading the full texts of the remaining 51 articles, 28 were excluded due to non-applicability/empirical nature, and 6 were excluded because AG/SG was not compared with non-AG/SG, resulting in a total of 17 eligible records.

The comprehensive breakdown of the selected articles, encompassing the distribution across years, country representation of first authors, and types of publications, is presented in Table 1. This tabulated information provides an insightful overview of the research landscape, shedding light on the temporal patterns, international collaboration, and scholarly outputs within the field of AR and VR technologies applied in museum learning.

Table 1

Distribution of Selected Articles

Distribution of selected articles		n (Frequence)	% (Percent)
Year	2012	2	3.92%
	2013	3	5.88%
	2014	5	9.80%
	2015	3	5.88%
	2016	3	5.88%
	2017	2	3.92%
	2018	5	9.80%
	2019	12	23.53%
	2020	5	9.80%
	2021	5	9.80%
	2022	11	21.57%
	2023	5	9.80%
Country	United States	11	21.57%
	Taiwan	7	13.73%
	United Kingdom	7	13.73%
	Other European countries	15	29.41%
Publication Type	Journal Articles	32	62.75%
	Conference Papers	11	21.57%
	Book Chapters	6	11.76%

Theses	2	3.92%

Table 1 presents the distribution of selected articles.The selected articles were published between 2012 and 2023. From 2012 to 2017, there were a maximum of five articles each year, while from 2018 to 2023, there were approximately ten articles per year. These results indicate an increasing research interest in the application of AR and VR technologies in museum learning. The first authors of the selected articles were predominantly from the United States (11 articles), Taiwan (7 articles), and the United Kingdom (7 articles). The remaining 15 articles were published by authors from other European countries. The distribution of the 51 selected publications is as follows: 32 journal articles (62.75%), 11 conference papers (21.57%), 6 book chapters (11.76%), and 2 theses (3.92%). All 51 articles were published in English.

Data Analysis

The selected research papers underwent a thematic analysis process to unearth prevalent themes and discoveries within the literature. This entailed a systematic method of coding and categorizing the information derived from the studies. The identified and analyzed themes were related to the applications of virtual museum and augmented reality museum, learning outcomes, teaching strategies, and technological considerations. The results were combined to provide a comprehensive picture of how these technologies influence learning outcomes in a museum environment.

It is crucial to acknowledge that the constraints and potential biases of the included studies were factored into the analysis process. The studies were scrutinized for their quality and rigor, and any inconsistencies or conflicting results were addressed. The approach of meta-synthesis permitted the integration of varied viewpoints and findings, thereby offering a thorough understanding of the topic. A coding framework was established to identify, distinguish, and extract pertinent information from the chosen studies. The coding parameters encompassed the timeframe and field of publication, types of learners, types of museums, learning domains, learning content, design elements or technological capabilities, technological devices, and learning outcomes.

Reliability

In this study, the coding framework was developed by the first two authors and validated by the third author. Two coders independently conducted the entire coding process.

Initially, each coder coded a subset of the studies and then underwent an intercoder coding to assess coding consistency. High consistency was found between the coders, and discussions were held to resolve any discrepancies. Subsequently, all data were fully coded, and the results were analyzed. This process follows a standard practice to ensure coding reliability.

Findings

Research Question (1): In which Contexts are AR and VR Technologies Used in Museum Learning?

This study aims to investigate the application of AR and VR technologies in the domain of museum learning, specifically addressing Research Question 1:

The participants in the selected articles mainly consisted of K-12 students (40%) and general public visitors (34%) who visit museums on a daily basis. Other studies focused on higher education students (17%) and adults (7%). Two studies included both university and K-12 students (Bossavit et al., 2018; Nechita & Rezeanu, 2019). Some researchers also paid attention to conversations among family members (Wang, 2014).

The majority of the selected studies (35.3%) were conducted in science museums (including science centers) and solely utilized AR technologies. Some studies focused on the use of AR and VR in art museums (25.5%), history museums (27.4%), archaeology museums (7.8%), and one study employed AR to deepen the understanding of medical specimens in a medical museum (Sugiura et al., 2019). Two studies involved the combined use of AR and VR in a history museum (Bell & Smith, 2020; Jung et al., 2016). In summary, AR and VR technologies are primarily utilized to support learning in science, history, and art museums.

AR and VR have found the most prevalent use in the domain of art education among the selected studies. In the museum context, these technologies have been primarily employed for enhancing art learning with 8 articles emphasizing AR applications and 5 focusing on VR applications. In the field of art education, AR and VR enrich the learning experience by introducing additional multimedia content to art collections, showcasing artistic talents in innovative ways, and providing a more enriched learning journey for visitors. Furthermore, these technologies find considerable use in the disciplines of history (11), biology (9), and physics (8). In historical education, these tools help recreate historical scenarios, such as the simulation of ancient Egyptian warfare or the recreation of the lives of ancient inhabitants of Brasov, Romania (Nechita & Rezeanu, 2019; Hammady et al., 2020). In scientific education, they aid in visualizing abstract concepts or phenomena not usually visible to the naked eye, such as demonstrating the correlation between the velocity of moving air and pressure using virtual arrows. Certain articles did not specify a particular domain (Jung et al., 2016; Salmi et al., 2017; Moorhouse et al., 2019; Haryani & Triyono, 2020). More information regarding the learning topics in the selected experimental studies can be found in the supplemental file. Jung et al. (2016) created two historical learning activities utilizing AR and VR technologies, while Bell and Smith (2020) facilitated biology and mathematics learning using both AR and VR.

AR and VR are primarily leveraged tools to boost declarative knowledge learning within museum environments. Examples include their use for imparting foundational knowledge on subjects such as rheumatoid arthritis, the principle of Bernoulli, or ancient civilizations (Wang, 2014; Yoon et al., 2017; Kosa et al., 2019; Khan et al., 2020). Additionally, they've been employed to hone thinking skills, including analytical and problem-solving capacities within gaming or adventure contexts, or for the study of the internal anatomy of a baleen whale. A mere pair of studies aimed at procedural-practical knowledge, such as sculpting, or intended to modify visitor behavior by presenting potent emotional narratives related to the Nazi Holocaust ((Takahashi et al., 2013; Guazzaroni, 2013; Hsu et al., 2018; Koutsabasis & Vosinakis, 2018; Poce et al., 2019; Borovanska et al., 2020). Two studies fostered emotional experiences by reenacting historical events, like ancient Egyptian warfare (Hammady et al., 2020). A single study sought to change visitor behavior through demonstrating the detrimental effects of smoking (Borovanska et al., 2020). There are, respectively, 1 and 7 studies that can be categorized under "Other" and "Not specified".

Research Question (2): What Design Elements Are Used in Conjunction With AR and VR Technologies in Museum Learning?

The second research question seeks to delve into the application of design elements in conjunction with AR and VR technologies for museum-based learning. It specifically investigates the ways these technologies are deployed to enhance the museum learning experience, with a particular focus on the integrated design elements and the specific technology devices used for their execution.

Drawing from the coding framework, studies implemented AR or VR to supplement physical exhibits with additional information, thereby enriching their content. The supplementary information was delivered via labels or texts, visual and auditory media or three-dimensional models, serving a function akin to labels found in traditional exhibitions (Damala et al., 2016; Ghouaiel et al., 2017; Juan et al., 2017; Connaghan et al., 2019; Borovanska et al., 2020; Tabone, 2020). Eight instances involved the use of these technologies to simulate or dynamically illustrate phenomena that would otherwise remain invisible, like the path and refraction of light or the pattern of electric currents across the visitor's body (Yoon et al., 2012; Oh et al., 2018). In scenarios where no physical objects or exhibits were available, AR and VR were utilized to recreate exhibitions, such as simulating floral patterns on a gallery floor via HMDs or presenting narrative scenarios like an underwater archaeological world for a more comprehensive understanding of marine life (Li & Chang, 2017; Harrington et al., 2019). Besides amplifying visitors' perspectives, a distinct advantage of AR and VR is the potential for interaction with virtual entities. From the examined studies, visitors had the opportunity to manipulate virtual objects which included interacting with 3D objects to observe climatic shifts via an AR application performing tasks as part of an examination (4), and facilitating content creation (4) like sculpting Kykladic figurines using traditional stone tools. Certain studies incorporated multiple design elements within a single article, using different design components to support a variety of learning activities (Jung et al., 2016; Hsiao et al., 2016; Dudzik, 2018; Koutsabasis & Vosinakis, 2018; Puig et al., 2020)

Mobile devices, comprising primarily of smartphones and tablets, emerged as the most frequently utilized technology in this context, appearing in 28 instances. The next most prevalent were Head-Mounted Displays (HMDs), featuring in 15 studies, with examples of such devices being Google Cardboard, HTC VIVE, and Microsoft HoloLens. Six studies leveraged desktop devices for this purpose, while projectors were employed in five instances. In two cases, the specific type of device used was not explicitly disclosed. It is worth noting that the total tally of devices surpasses 51 as certain studies opted to use multiple devices either for crafting diverse activities or to establish a more effective learning environment (Jung et al., 2016; Dudzik, 2018; Nechita & Rezeanu, 2019; Sugiura et al., 2019).

Primarily, portable devices such as smartphones and tablets were the tools of choice for Augmented Reality (AR), mainly aiming to enhance the understanding of physical exhibits (19). Visitors were able to utilize AR functionalities by scanning exhibits or QR codes, or even by overlaying digital enhancements onto real-world objects using their mobile devices. To illustrate, users could scan a table using their mobile camera, subsequently gaining access to related commentary and information (Chang et al., 2014). The next stage involved creating visualizations of intangible or hidden events, using a range of tools including desktop computers (4), projection systems (2), and head-mounted displays or HMDs (1). In the context of exhibitions lacking physical artifacts, simulations were brought to life via HMDs (3) and mobile devices (3). One particular example is the creation of immersive narrative experiences using HMDs, such as underwater archaeological sites, enhancing the visitor's understanding of marine life (Li & Chang, 2017).

A unique aspect involved the use of mobile devices (4) for running quiz-based games. For instance, the study by Savela et al. (2020) utilized mobile AR applications where users could visualize hovering question marks above related exhibits and then navigate the exhibition area to address all the quiz items. Lastly, the opportunity for visitors to craft their own content was facilitated through the use of mobile devices (1), projectors (1), or stationary computers (1). To exemplify, visitors were able to simulate the work of an ancient craftsperson using a kinesthetic application for sculpture making, allowing them to replicate Kykladic figurines using prehistoric stone tools (Koutsabasis & Vosinakis, 2018).

The findings show that mobile devices, such as smartphones and tablets, are predominantly utilized for AR, with visitors able to view digital augmentations through apps installed on their devices. Head-mounted displays (HMDs) were employed equally for both AR and VR. AR HMDs, like Google Cardboard and Google Glass, are typically low-immersion devices that allow users to interact with the physical world while viewing digital overlays. In contrast, VR HMDs, like HTC VIVE or Samsung Gear VR Glasses, offer a high degree of immersion, fostering a sense of full presence within a virtual environment (Connaghan et al., 2019; Borovanska et al., 2020). Desktop devices, which include stationary computers or equipment located within the museum, were primarily used for AR, displaying digital augmentations once visitors interacted with exhibits. The solitary VR instance involving a desktop device included the use of a handheld device named Leap Motion Orion (Yoon & Wang, 2014; Koutsabasis & Vosinakis, 2018; Yoon et al., 2018). Projectors in AR applications were used to provide feedback or to display physical events in conjunction with desktop devices. Projectors in VR applications were paired with a Kinect device, facilitating full immersion for learners (Yoon et al., 2013; Bossavit et al., 2018; Dudzik, 2018).

Research Question (3): What are the Effects of AR and VR Technologies on Museum Learning?

The effects of AR and VR technologies on museum learning, addressing research question 3 "What are the effects of AR and VR technologies on museum learning?", are multifaceted. These technologies impact learners' academic achievement and foster positive perceptions of the learning experience, illustrating the potential of these tools in a museum context.

The investigation reveals that the application of AR and VR in museum learning environments leads to promising results. These technologies facilitate immersive and enriching learning scenarios, adhering to the principles of experiential and situated learning, which have been established as effective educational methods. Through AR and VR technologies, learners are encouraged to actively participate in cognitive processing, constructing coherent mental representations based on their personal experiences. Although the learning content remains similar across groups, learners exposed to AR and VR tend to outperform their peers in the non-AR/VR control group. This difference can be traced back to the dynamic visualization and rich informational content provided by AR and VR, offering additional stimuli that enhance learning outcomes (Kolb, 2014; Mayer, 2014).

The noted effects on academic achievement align with prior reviews that underscored the effectiveness of AR technologies in general educational contexts. Beyond that, the influence of AR and VR transcends mere knowledge acquisition, affecting changes in visitors' interests, beliefs, attitudes, and even their behavior during museum visits. The innovative nature of AR and VR captivates visitors' attention, stimulates their engagement, and fosters persistence in the learning process, thereby contributing to more favorable perceptions of the museum experience (Bacca et al., 2014; Schwan et al., 2014; Bettelli et al., 2020).

In conclusion, the impact of AR and VR technologies on museum learning is multifaceted, promoting academic achievement and positive perceptions among learners. These technologies create immersive and interactive learning environments, enabling learners to actively partake in cognitive processes and construct significant mental representations. The integration of AR and VR in museum contexts has the potential to facilitate efficient and captivating learning experiences, thereby advancing the field of museum education and boosting the overall learning outcomes for visitors.

Discussion and Results

The meta-synthesis review reflects a growing interest in the implementation of AR and VR technologies in museum education, especially within the last three years. Predominantly, studies have targeted K-12 students. This trend is unsurprising given the significant role museums traditionally play in the informal education of this demographic, facilitating various activities and enriching their life outside school. However, there's a dearth of studies involving teachers who could provide valuable insights on improving AR and VR integration in museum learning based on firsthand experiences.

In the realm of learning domains, AR and VR technologies find common use in art, science, and history education. For items like artworks, historical exhibits, collections, and artifacts which often necessitate a more engaging presentation, AR and VR technologies offer digitally augmented visual enhancements to the details of artworks. Previous studies have suggested that learners can better grasp abstract and challenging scientific concepts, for instance, Bernoulli's principle, with the help of AR. AR can make the underlying, often invisible mechanisms of complex phenomena more understandable. Regarding learning content, most studies have concentrated on the development of factual or conceptual knowledge, somewhat overlooking the potential of AR and VR to support learning. AR and VR can provide simulation environments for learners to master practical skills such as sculpting, enhance higher-order thinking skills, or foster an emotional connection or experience (Cai et al., 2013; Chang et al., 2014; Chiu et al., 2015; Yoon et al., 2017). However, the number of studies on how AR/VR-supported museum learning can facilitate the acquisition of these outcomes is comparatively scarce.

Research findings indicate that AR technologies are more prevalent in museum learning compared to VR technologies, likely due to the ease of access to necessary devices. Advances in mobile technologies like smartphones and tablets have made AR applications available to the general public through built-in cameras, global positioning systems, and internet connectivity. Additionally, AR devices are more cost-effective and user-friendly compared to VR devices which have not yet gained widespread acceptance in museums (Sommerauer & Müller, 2014). The technological potential of AR and VR for museum learning includes placing information on physical exhibits or objects (23 studies), simulating complex phenomena or abstract concepts (8 studies), simulating exhibits (7 studies), and simulating narrative scenarios (6 studies). Enhancing understanding of exhibits like historical artifacts and gaining detailed information are fundamental aims of museum visits. However, in cases where adding paper labels to exhibits is impractical, like observing tumor structure and development in a medical museum, digitally placing information on physical exhibits becomes possible. Moreover, digitally simulating phenomena, exhibits, and narrative scenarios is ideal for immersive and experiential learning (especially in science museums) and enhancing scientific literacy. But few studies have explored how AR and VR can be implemented to enhance visitor interaction with exhibits or enable visitors to generate virtual content in immersive environments suggesting that the application of AR and VR mainly takes place in low-immersion modes (Crowley et al., 2014; Hsiao et al., 2016; Koutsabasis & Vosinakis, 2018).

The rich and immersive learning environments fostered by AR and VR can be attributed to the facilitation of experiential or situated learning, as learners actively engage in cognitive processing when constructing a coherent mental representation of their own experiences. Moreover, even with nearly identical learning content, learners in the AR and VR experimental group often benefit from dynamic visualizations containing more information, resulting in superior performance. These findings align with a previous review emphasizing the effectiveness of AR technologies in general educational settings. While museum visits' learning outcomes involve knowledge acquisition in a strict sense, they also encompass shifts in visitors' interests and beliefs. Museum visits are hoped to impact visitors' attitudes and even their behavior. The technical novelty of AR and VR can attract visitors, capture their attention, and inspire persistence in learning, leading to more positive perceptions (Bacca et al., 2014; Kolb, 2014; Mayer, 2014; Schwan et al., 2014; Bettelli et al., 2020).

The study presents some limitations. Firstly, the review only considered articles from four databases, namely Web of Science, Scopus, IEEE Xplore, and ProQuest, potentially overlooking relevant studies not included in these four databases. Secondly, this study focuses on traditional museums, neglecting various informal learning environments like zoos, aquariums, arboretums, and historical sites that have broadened the concept of "museum". The application of AR and VR to these types of museum learning environments was not covered in this study. Hence, future research should extend to these types of museums to comprehensively evaluate the impact of AR and VR on museum learning. Thirdly, this review did not examine barriers to AR and VR usage in museum learning, as some articles reported common disadvantages like dizziness and device burden, which could influence the learning impact.

The existing empirical studies also pose some issues. Firstly, some studies merely provided a cursory background introduction and lacked detailed explanations of AR and VR implementation in museums. Secondly, the majority of studies did not include control groups to investigate the impact of AR and VR in museum learning. Thirdly, the real impact of museum visits might not be evident, as the typical museum learning experience with AR and VR lasts a few hours or less, and current studies have mainly evaluated immediately observable learning outcomes of visitor participants, excluding distal outcomes like long-term interest in science or art among youth (Bell & Smith, 2020).

This study provides a meta-analysis on how AR and VR technologies are employed to support museum learning, their integration into learning activities, and their effects on academic achievement. Firstly, the results indicate that AR and VR are commonly utilized by K-12 students in science and art museums, primarily for acquiring declarative knowledge. Secondly, AR and VR are frequently employed to add supplemental information to physical exhibits, dynamically visualize typically invisible phenomena or concepts, and simulate virtual exhibitions and narrative scenarios. Only a handful of studies have employed AR and VR to enhance visitor interaction with exhibits. Lastly, this meta-synthesis research demonstrates the positive effects of AR and VR applications on both academic achievement and learner perceptions. These findings can contribute to a deeper understanding of AR/VR-supported learning in museums.

Recommendations

1. Broadening the scope of educational content in museums: A notable majority of extant studies have primarily centered on the procurement of factual knowledge, such as rudimentary information on artists and their works. The acquisition of procedural or practical knowledge and analytical thinking abilities, on the other hand, has been given relatively less focus. Consequently, prospective research should aspire to include these elements as educational objectives.

2. Offering genuine immersive experiences: In order to fully harness the potential of VR technologies, museum education environments ought to endeavor to provide authentic immersive learning experiences. Merely displaying animations on less immersive desktop

devices does not fully utilize VR's capabilities, calling for a joint effort between museum education designers and tech experts.

3. Accounting for cognitive abilities across varying age groups: Museum visitors of differing age groups demonstrate a range of cognitive skills, technology usage habits, and museum visit preferences. Therefore, it is critical that future research recognizes these variations and accommodates the wide-ranging needs of visitors.

4. Employing controlled experimental designs: To effectively evaluate the impacts of AR and VR technologies on museum education, such as knowledge acquisition and skill development, there is a pressing need for an increase in experimental or quasi-experimental research.

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