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IMPLEMENTATION OF VIRTUAL REALITY IN CONSTRUCTION EDUCATION: A CONTENT-ANALYSIS BASED LITERATURE REVIEW

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Silvia Mastrolembo Ventura, PhD
University of Brescia, Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM)
silvia.mastrolemboventura@unibs.it

Fadi Castronovo, PhD
University of Brighton, School of Architecture, Technology and Engineering
f.castronovo2@brighton.ac.uk

Dragana Nikolić, PhD
University of Reading, School of Construction management and Engineering
d.nikolić@reading.ac.uk

Angelo L.C. Ciribini, Prof.
University of Brescia, Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM)
angelo.ciribini@unibs.it

SUMMARY: In construction education many research initiatives have explored the adoption of innovative and interactive learning experiences for improving the visual, analytical and problem-solving skills of students. Virtual *reality (VR), in particular, has been increasingly viewed as a promising way for students to dynamically interact with information, to test concepts in a visual and intuitive manner and, through real-time feedback, to begin to construct their knowledge and spatial skills. However, with the proliferation of consumer market VR devices and headsets, the question of their appropriateness and specific benefits for construction education becomes even more important and educational VR applications still fall short of offering straightforward VR solutions to consistently realize the said benefits. This also reveals a host of conceptual and empirical challenges in how VR for construction education is conceptualized and justified. This study proposes an extensive review of the literature to identify and discuss contextual factors and trends in VR implementation for construction education in relation to three main foundations: (1) educational theoretical foundations, (2) methodological foundations and (3) technological foundations. A content analysis-based approach is adopted to identify and discuss key research themes. Results from the literature review have provided an insight into the current efforts of the implementation of virtual reality into pedagogy. It has provided a timeline of how such implementation has changed throughout the last twenty years. In addition, this study provides a unique perspective of the methodologies deployed in this research topic as well as an overview of the technological configurations adopted for VR use cases in the construction education domain. Based on these achievements, this study aims to pave the way for new research opportunities in the application of VR in construction education.*

KEYWORDS: *virtual reality, construction education, level of immersion, cognitive processes, learning theories, VR use cases, content analysis review*

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1. INTRODUCTION

Students in early construction education are challenged with visualizing and understanding often complex design systems and structures, and one of the main goals of construction education is to help students to develop such skills. Visualization skills are seen as part of what is broadly defined as spatial cognition, which refers to how people acquire and use knowledge about spatial environments. More specifically, studies in psychology provide guidance on visual perception and spatial cognition and their purpose to identify, estimate, or otherwise give meaning to perceived objects and spaces (Palmer, 2003) by storing, recalling, creating, and communicating spatial images (Osberg, 1997).

In the architecture, engineering and construction (AEC) context, spatial cognition has been variously described as the ability to understand the proportions of a given space (Pinet, 1997) or to orient in a given space (Henry and Furness, 1993). Then it follows that developing spatial cognition skills is necessary in order to generate and evaluate proposed design and construction solutions. In these processes, students can now adopt a combination of different representational media – from static two-dimensional (2D) drawings to more dynamic three- (3D) and four-dimensional (4D) models - that offer new ways of exploring construction information. Studies that have explored the role of representations for spatial understanding (e.g., Rice, 2003), in fact, typically argue that physical scale models or two-dimensional drawings are limiting in accurately representing three-dimensional objects. Because of the reduced or abstracted scale and object representation, these forms require the user to exert more effort to visualize objects, spaces and the movement through them (Dorta and LaLande, 1998). Thus, visualization that includes time and motion conveys spatial information more easily, allowing the designer to make better judgments about space and form (Kalisperis et al., 2002).

1.1 Virtual reality in construction education

Within this context, in construction education, improving visual, analytical and problem-solving skills of students has prompted many initiatives that explore innovative and interactive learning experiences such as virtual reality (VR). Virtual reality is a computer-simulated environment where users can explore, experience and evaluate a full-scale virtual prototype in an intuitive and engaging manner through immersion and sense of presence (Bordegoni and Rizzi, 2011; Paes at al, 2017). Based upon the point-of-view of participants and the extent to which their visual field of view is covered, virtual reality can be broadly categorized into non-immersive and immersive systems. The attribute of physical, or visual immersion has been also associated with the concept of spatial presence, or “the sense of being in an environment” (Kober et al., 2012). Immersive environments, therefore, by covering the entire field of view of users allow participants to feel as though they are inside the environment. Conversely, non-immersive environments only allow participants to see the contents based on how the device in use – desktop, smartphone, or tablet – is held and moved. Moreover, immersive environments can be also classified in semi- and fully-immersive VR. The former is an experience where a portion of the field of view of the user is covered by the system; the latter is an experience where the entire field of view of the user is covered by the system thus increasing the sense of presence within the virtual prototype (Mastrolembo Ventura et al., 2020).

Research in virtual reality and its adoption in the AEC industry has substantially grown in recent times, paralleling an increase in offer of low cost, scalable solutions and wearable head-mounted displays (HMD), such as OculusRift, HTC Vive or even Google Cardboard. At the same time, the knowledge of what makes each of these different VR systems and configurations appropriate for a particular use scenario is tied to the specific characteristics of these systems (e.g., single-user vs. multi-user, immersive vs. non-immersive, stereoscopic vs. monoscopic, etc.), and the nature of the tasks and their users (Whyte and Nikolić, 2018). Research exploring the benefits of virtual reality for general task performance have focused on investigating the effects of specific system components, such as field of view (Arthur, 2000), head tracking and stereoscopy (Ragan et al., 2013), or navigation (Balakrishnan, 2008) on spatial understanding and user performance. Other studies have attempted to differentiate and compare VR configurations, such as fully-immersive room-like systems, such as CAVE, with non-immersive systems, such as desktop (Swindells et al., 2004). The assumption or the assertion that immersive systems are advantageous for spatial understanding (Paes et al., 2017) stems mostly from the notion that such systems provide multiple depth cues that are missing from non-immersive systems. Moreover, the ability to view the model at full scale, such as in fully-immersive systems (e.g., head-mounted displays or room-like VR) is argued to support egocentric experience of the spaces and thus, understand better the relative sizes of spaces to their own scale. In other words, when the scale of the representational medium does not match that of the observer, the viewer is more prone to misinterpret objects and spaces resulting in design errors (Kalisperis et al. 2002).

Virtual reality has been increasingly viewed as a promising way for students to dynamically interact with information, test concepts in a visual and intuitive manner and, through real-time feedback, begin to construct their knowledge and spatial skills (Castronovo et al., 2017a). Moreover, as design and construction processes work with visual and spatial data, they are considered as an ideal context for studying the effects of VR and simulation technology on spatial cognition in construction education. Earlier studies have argued that virtual reality is a superior learning environment for enhancing spatial skills because of its nature to maintain visual and spatial characteristics of the simulated world (e.g., Regian, 1997), whereas Dwyer et al. (1994) also emphasized how virtual reality provides an engaging environment that is stated to have a positive effect on the motivation of students and their learning. This affective aspect of VR has similarly propelled simulation games as learning experiences that straddle the pedagogical objectives and elements of fun to encourage student motivation and promote deeper learning. Prior studies have confirmed VR-based simulation to be consistently more effective than low-engagement forms of training, such as lectures, images, or videos (Robson et al., 2010). What tends to make these learning experiences more effective compared to traditional instruction is that they allow students to fail, but through in-process reflection, which allow students to modify their strategies and repeat the process until reaching the goal. The intuitive, iterative, interactive, and fail-safe aspects of such learning experiences can increase their motivation and encourage students to invest time practicing their skills, deemed essential for effective learning (Aldrich, 2003; Chen and Levinson, 2006). For this reason, construction education research has been exploring both virtual reality and game engines as platforms that bring interactive and motivational aspects to engage students in simulating various real-world scenarios for a range of tasks (Castronovo et al., 2019; Castronovo et al., 2018a; Castronovo et al., 2017a; Lee et al., 2014; Lee et al., 2011). This view of learning, where students build their knowledge through cyclical interactions and feedback, gave way to problem-based, project-based or active learning approaches, which place emphasis on process and perception, rather than on memory.

Educational VR-based simulations, in most instances, are developed and used for design visualization (e.g., Castronovo et al., 2020; Nikolić and Windess, 2019; Nikolić, 2007), construction safety training (Le et al., 2015; Sacks et al., 2013), equipment operation, and structural analysis (Abdelhameed, 2013). Some of the studies reveal that virtual reality, though generally valuable for spatial understanding, cannot be treated as a singular concept when it comes to evaluating its effectiveness for educational tasks that differ in their objectives. Given the importance that both a representation and a medium have in the process of visualization, studies have sought to understand how specific characteristics and attributes of visualization experiences could affect and enhance the learning process (e.g., Castronovo et al., 2020; Nikolić and Windess, 2019; Nikolić, 2007). For example, in the study reported by Sacks et al. (2013), the semi-immersive power-wall setting offered significant advantages in maintaining the attention and concentration of trainees for stone cladding and cast-in-place concrete tasks, though less so for general safety knowledge. At the same time, the study raised questions around the suitability of group-based training using a power-wall for what should rely on first-hand experience and, thus possibly the use of individual VR configurations. In their research, Castronovo et al. (2017b) evaluated the value perceived by students for performing VR-enabled design reviews and found that the VR systems had a significant impact on their spatial presence, immersion, and enjoyment. This demonstrates examples where VR could enhance the visualization process by augmenting the richness and recall of the information (Osberg, 1997).

While some of the recent studies exploring the value of such systems for design reviews, constructability or safety training are primarily qualitative in nature, fewer experimental, comparative and user-centered studies reveal a general gap around human factors such as spatial cognition (Paes et al. 2017) and the value of immersion for data visualization (Schuchardt and Bowman, 2007). For example, studies by Nikolić (2007) and Zikic (2007) compared how using semi-immersive large screen configurations and monitor-based configurations influence viewers in estimating the size of spaces and objects in VR, revealing a more complex interplay between the VR variables such as field of view, stereoscopy, screen size, levels of detail and realism on spatial understanding. Namely, the findings revealed how certain variables work in tandem (e.g., screen size and stereoscopy) leading to significant overestimation of height or depth. In the context of undergraduate architecture education, the findings of these studies suggested the usefulness of having large screens and wide field of view for evaluating spaces in terms of scale and size, as long as detail and realism are kept at low levels. These examples reveal how the pedagogical aspects require carefully crafted simulation scenarios where attention, motivation, and engagement are key to sustained learning. Equally, technological aspects of interactivity, feedback, and immersion depend on the pedagogical goals and considerations that aim to place the learner in an active role, rather than as an observer.

Still, with the proliferation of consumer market VR devices and headsets, the question of their appropriateness and specific benefits for construction education become even more important. One of the current challenges from the research view is that virtual reality still tends to be largely conceptualized as a singular construct, where the often-proclaimed benefits tend to mask the underlying perceptual complexities of different configurations these technologies carry. In all VR application cases, certain choices are made about which salient features of either content representation or the technology configurations are included, albeit not always explicitly. The issues of representations and media are intrinsically coupled, making it particularly challenging to discern the combinations of specific features and attributes that amplify, rather than hinder and distract from an effective experience or task performance. Consequently, due to contextual variations and their distinctive features, educational VR applications still fall short of offering straightforward VR solutions to consistently realize the said benefits. This also reveals a host of conceptual and empirical challenges in how VR for construction education is conceptualized and justified from the pedagogical, methodological and theoretical perspectives.

1.2 Research question and structure of the paper

The challenges that have been presented raise several questions in relation to the nature of the learning tasks that drive the use of VR as well as in reference to the most suitable VR configurations that can be discerned as influential in support of achieving the learning outcomes. Moreover, what empirical evidence is there to support the claims made for VR benefits in construction education? What empirical evidence is there to support the claims that the use of VR has an impact on how students learn and when?

For this reason, the goal of this study is to answer a broad question about the current state of VR implementation of VR in construction education. Specifically, the contextual factors for VR implementation are explored and identified in addition to understanding the next steps in the applications of virtual reality in construction education. To achieve this goal, the study asks:

1. What is the current state of research on the application of virtual reality in construction education?
2. What are the educational theories that have leveraged in the application of virtual reality in education?
3. What are the research methodologies that have been used in the application of virtual reality in construction education?
4. What kind of technology has been adopted in the application of virtual reality in construction education?

To address these questions, an extensive review of the literature has been carried out based on content analysis to identify and discuss contextual factors and trends in VR implementation for construction education in relation to three main foundations: (1) educational theoretical foundations, (2) methodological foundations and (3) technological foundations. The second question aims at understanding how current literature in construction education underpins or aligns with educational psychology theories (e.g., constructivism, learning-by-doing, etc.) and educational design practices (e.g., use case design, learning outcomes design, etc.). The third question aims at evaluating the trends in research methodologies deployed when investigating the adoption of VR in construction education. For this question, the content analysis aims at identifying the type of research (e.g., qualitative versus quantitative), the sample size of the studies, the selected population, and the dependent versus independent variables that were measured. The last question aimed at surveying the type of technology and set-ups that have been adopted in the last two decades of research.

By answering these questions, this study aims to pave the way for new research opportunities in the application of VR in construction education.

2. RESEARCH METHODOLOGY

2.1 Paper retrieval

This study proposes a three-stage review methodology (Figure 1) based on content-analysis as adapted from Mok et al. (2015). The content analysis-based review method, in fact, is widely applied in the research field of engineering and construction management (Wang et al., 2018).

In Stage 1, a comprehensive desktop search for relevant publications was conducted under the "title/abstract/keyword" field of a commonly applied search engine and academic database, Scopus. Literature search keywords were used, and they include *virtual reality, construction, education*. The search rule was: [VR OR "virtual reality"] AND construction AND education. The string of keywords was deliberately wide. The aim, in fact, was to get a large dataset of previous literature to analyze data about the implementation of virtual reality in education without approaching the topic in relation to contents other than that of the application domain (i.e., construction). Papers with these specific terms included in the title, abstract, or keyword were considered to have fulfilled the requirements of this research study. Moreover, the scope of publication search was scaled down to a time span of 2000-2021 (October, 26th). The authors selected this timeframe because relevant publications appeared since the early 2000s and they suggested that the state-of-the-art of VR implementation in construction education could be clearly depicted by reviewing conference proceedings and academic journals of this time span. The literature search was then limited to papers published in the English language. The search was further limited to subject areas such as engineering, computer science, social sciences, decision sciences, business, management and accounting with the document type of article, review or conference paper. Journal and conference proceedings were selected as document sources. Previous content-based review studies suggest eliminating conference proceedings from the search "to ensure that all retrieved papers could be investigated using an identical analytical construct in terms of research aims and methodologies" (Li et al., 2018). However, most of the studies published on this topic internationally are in the form of conference papers and for that reason they are included in the search to evaluate how the research has developed through the years included in the selected research time span. Moreover, a manual search was conducted as a means to complement the possible omission of papers archived by the search engine. As a result, a total of 393 papers related to VR in construction education were identified.

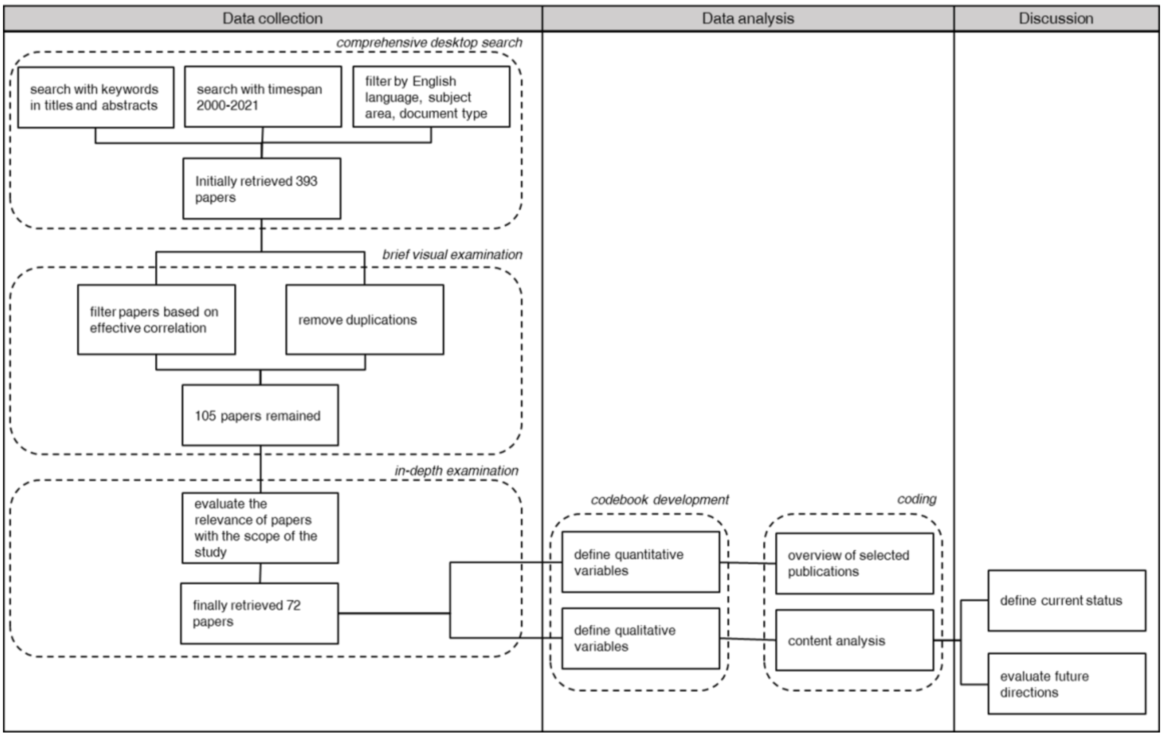


FIG. 1: Research framework of this study

A downside of using such a wide string of keywords is that some of the results collected were not effectively correlated with the scope of the analysis. For example, they did not focus on the construction sector despite having the word "construction" in the title, abstract or keywords. For that reason, Stage 2 filtered the results from Stage 1 based on the effective correlation of the papers to the scope of the study. Irrelevant papers among the retrieved publications were excluded from the results after a brief visual examination of the content of the article. Duplications were also deleted, and a total number of 105 publications was selected for further analysis. Stage 3 was the last phase of data collection. It was related to the deep reading of the publications selected in Stage 2 in order to exclude less relevant papers (e.g., low quality, same studies published more than once).

Finally, 72 publications were considered as significant for the analysis within the scope of this paper. The three-stage search may not guarantee a comprehensive coverage of the papers that are worth reviewing. However, such an approach suffices for providing a considerable amount of significant research works from which the study could generalize findings and recommend future directions.

2.2 Overview of selected publications

The selected publications were analyzed based on a set of quantitative and qualitative codes: 6 quantitative codes and 13 qualitative codes are selected and defined (Table 1). The codes are adapted from and integrate a few similar studies using content analysis, such as Song et al. (2021), Li et al. (2018), Mok et al. (2015) and Yi and Chan (2014). Quantitative codes are adopted by the authors to provide an overview of the retrieved publications (i.e., year, author, article title, journal, conference, country scientific production). For the definition of qualitative variables, an initial coding scheme was used (i.e., type of study, population type, population sector, research methodology, results, emergent themes, limitations). The initial coding scheme was developed prior to data analysis and then, as the analysis proceeded, additional codes were developed applying an inductive approach to revise and refined the initial coding scheme The qualitative section of the codebook of recurring categories evolved over the course of the literature review to incorporate aspects that were not initially taken into account (i.e., use case, cognitive domain, learning theory, technology configuration, VR content, mode of interaction). The coding process was then performed repeatedly to increase reliability. Moreover, qualitative codes were considered as independent variables in the light of which the goal and impact of using VR in construction education (i.e., dependent variables) was evaluated and discussed.

Table 1: Codebook for content analysis of this study

Code	Definition of code
Quantitative variables coded	
Year	Year of publication
Author	List of authors
Article title	Title of the article
Journal	Publication in which the journal article was published
Conference	Publication in which the conference paper was published
Country scientific production	Where the research is taking place
Qualitative variables coded	
Type of study	VR implementation and assessment paper; VR development paper
Population type	Undergraduate, graduate, mixed
Population sector	Architecture, construction, mixed
Use case	Learning subject through VR implementation
Cognitive domain	Learning outcomes based on revised Bloom's taxonomy
Learning theory	How students receive, process, and retain knowledge during learning
Technology configuration	Non immersive, semi-immersive, fully-immersive
VR content	e.g., BIM model, 3D model, 360-degree-scenes, game
Mode of interaction	Vision, audio, touch, smell
Research methodology	Quantitative, qualitative, mixed
Results	Key results of papers and outcomes of research
Emergent themes	Themes identified in the literature not initially nominated for examination
Limitations	Methodological and conceptual limitations of the research
Dependent variable(s)	The goal and impact of using VR in construction education

It was found that previous studies include 42 publications in conference proceedings (Table 2), while 30 research works are reported in journal articles (Table 3). Moreover, a high number of conference papers were presented in the ASEE (American Society for Engineering Education) Annual Conference and Exposition (9) and in the ASCE (American Society of Civil Engineers) International Conference on Computing in Civil Engineering (4). Journal articles are mainly published in Automation in Construction (3), in the International Journal on Information Technology in Construction (3) and in the Computer Application in Engineering Education journal (3). Moreover, Figure 2 (left) shows the annual number of relevant conference papers and journal articles published yearly from 2000 to 2021. As it can be seen from the graph, the first studies on the adoption of virtual reality for construction education date back to the early 2000s. As hypothesized, these works were initially published in the form of conference papers, but recently there has been an increase in the publication of journal articles on the subject, reflecting not only a quantitative focus, as can be seen from the constant increase in the number of publications produced from 2000 to 2021, but also a qualitative focus on the subject, its analysis and in-depth study.

Table 2: Distribution of selected conference papers

Conference	Number of selected papers
ASEE Annual conference and exposition	9
ASCE i3CE - International conference on computing in civil engineering	4
ASCE CRC - Construction research congress	3
IEEE EDUCON - Global engineering education conference	3
IASTED - International conference on applied simulation and modelling	2
IEEE TALE - International conference on teaching assessment and learning for engineering	2
IADIS - Conference on computer science and information systems	2
IV - International conference on information visualisation	2
ISARC - International symposium on automation and robotics in construction	1
CIB W78 - International conference of the CIB commission W78 on Information Technology for Construction	1
ACADIA - Conference of the association for computer aided design in architecture	1
CSEDU - International conference on computer supported education	1
ECT - International conference on engineering computational technology	1
ETCS - International workshop on education technology and computer science	1
HSI - Conference on human system interaction	1
IEEE Virtual reality	1
TMCE - International Symposium on Tools and Methods of Competitive Engineering	1
ILRN - International conference of the immersive learning research network	1
International journal of engineering education	1
ISEC - International structural engineering and construction conference	1
Procedia computer science	1
VISIGRAPP - International joint conference on computer vision imaging and computer graphics theory and applications	1
WSCG - International conference on computer graphics visualization and computer vision	1
Total	**42**

Table 3: Distribution of selected journal articles

Journal	Number of selected articles
Automation in Construction	3
Journal of Information Technology in Construction	3
Computer application in engineering education	3
International journal of construction education and research	2
International journal of emerging technologies in learning	2
Journal of professional issues in engineering education and practice	1
Engineering, construction and architectural management	1
Alexandria engineering journal	1
International journal of architectural research	1
British journal of educational technology	1
Educational technology and society	1
Interactive technology and smart education	1
International journal of environmental research and public health	1
International journal of online engineering	1
Journal of architectural engineering	1
Journal of construction education	1
Journal of construction engineering and management	1
Journal of intelligent and robotic systems: theory and applications	1
Open house international	1
Universal access in the information society	1
Journal of computing in civil engineering	1
International journal of engineering education	1
Total	**30**

In addition, Figure 2 (right) shows the average number of citations per year. One or more research works published in 2016 are collecting the highest number of average total citations per year. One or more publications in 2010, 2015 and 2018 also have an impact on the topic. Pedro at al. (2016) developed a framework for construction safety education through interactive virtual reality claiming that the system offers an innovative medium for experientially improving hazard identification ability, transferring safety knowledge, and engaging students. Sampaio et al. (2010) is the first journal article published on the subject after two other examples dating back to nine years earlier. They developed “didactic interactive models showing construction works” to “assist in the study of the necessary equipment needed and how it functions on site”. Le et al. (2015) developed a simulation prototype based on the platform of Second Life to teach students about construction safety with an experiential learning approach. Wang et al. (2018) proposed the first review published as a journal article about the use of virtual reality in construction engineering education and training.

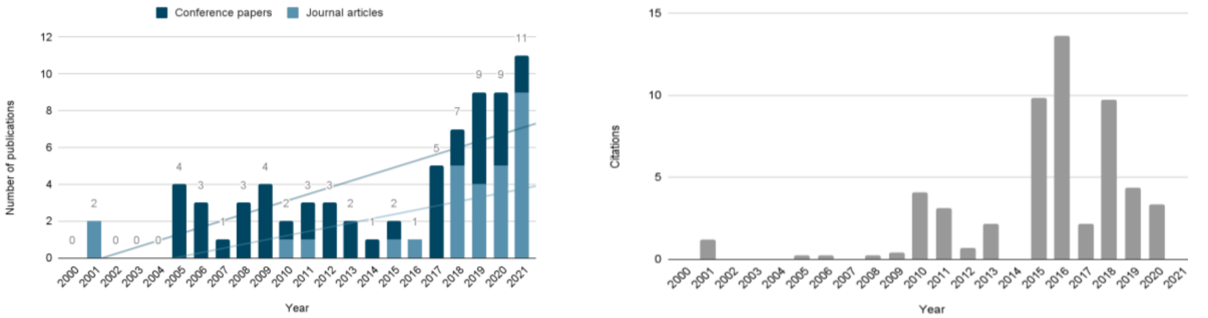
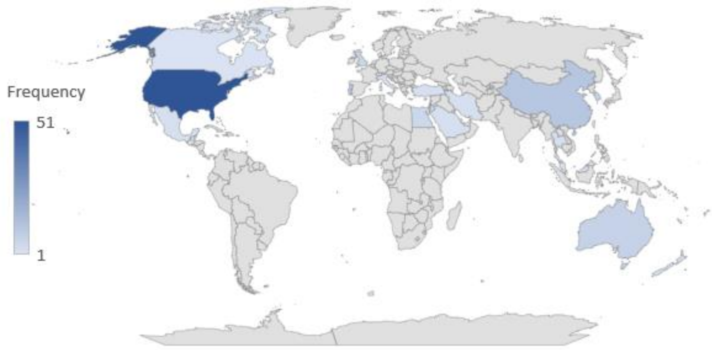


FIG. 2: Number of relevant papers published yearly from 2000 to 2021 (left). Average number of citations per year of the selected publications (right).

Finally, Figure 3 represents the scientific production of countries leading research in the area of virtual reality implementation for construction education. The leading role of the United States affiliations in research on the adoption of virtual reality in construction education is evident, as it is also evidenced by the number of research papers published in US conferences as the ones organized by ASEE and ASCE (Table 2).



Rank	Country	Frequency	Rank	Country	Frequency	Rank	Country	Frequency
#1	United States	51	#8	Israel	3	#15	Taiwan	2
#2	China	11	#9	Jordan	3	#16	Iran	2
#3	Portugal	10	#10	Italy	2	#17	Thailand	2
#4	Australia	7	#11	Malaysia	2	#18	Turkey	2
#5	South Korea	6	#12	Mexico	2	#19	Netherlands	1
#6	United Kingdom	5	#13	New Zealand	2	#20	Canada	1
#7	Egypt	5	#14	Saudi Arabia	2	#21	Bahrain	1

FIG. 3: Country scientific production. Different shades of blue indicate different productivity rate: dark blue = high productivity; grey = no articles).

2.3 Content analysis

This study adopts content analysis, a structured and systematic technique to identify key research themes for literature review. This methodology is used for data reduction to facilitate analysis of large quantum of textual data by adopting protocols that facilitate the achievement of reliability and interpretive validity (Laplume et al., 2008). It can be used both quantitatively (e.g., frequency counts, correlations, trends, and differences over time) and qualitatively (e.g., theme identification, theory elaboration) (Laplume et al., 2008). The coding was done using a codebook adapted from Mok et al. (2015) and partially inductively derived. Within-theme and between-theme comparisons were used to identify and elaborate themes. To ensure reliability, multiple rounds of coding were conducted and followed by discussions that led to refinement of the codebook. Random checks conducted on articles on completion of coding pointed to high coding accuracy (Laplume et al., 2008).

The selected articles were reviewed and relevant codes and categories for content analysis were defined. In this phase of the research, it was decided to exclude review papers (i.e., 4 papers) from the coding process of qualitative variables, which has been focused on empirical research works (i.e., 68 papers). Previous review papers were published from 2014. In particular, Keenaghan and Horváth (2014) proposed the first review about the implementation of VR technologies in built environment education, including a focus on their educational usability and effectiveness. They found that the literature does not specifically address the issue of learning experience when different virtual reality technologies are used, but it does emphasize the importance of usability evaluation to enhance the effectiveness of applications. Wang et al. (2018) reviewed the use of virtual reality in construction engineering education and, moreover, they extended their review to the training use case. They selected two codes for content analysis in their review: (1) technology (i.e., desktop-based VR, immersive VR, 3D game-based VR) and (2) applications (i.e., architecture visualization and design education, construction safety training, equipment and operational task training, structural analysis education). Wen and Gheisari (2020) reviewed virtual field trip applications in construction education while specifically focusing on the construction subject areas, technology use, and learning assessment techniques used in those virtual field trips. Finally, Sirror et al. (2021) presented a study on VR and its applications in architecture education, including design, construction, surveying, and structural analysis. The study was based on the assumption that the VR experience could motivate students to learn, especially in a contemporary context as the one affected by the Covid-19 emergency and the related need for the adoption of e-learning solutions.

This study differs from previous review papers about VR implementation in construction education because it integrates the individual findings from previous reviews by adopting an extended codebook and by adding additional perspectives such as the impact of virtual reality adoption on cognitive processes and learning theories.

3. CRITICAL REVIEW OF PREVIOUS STUDIES

The critical review of previous studies provided that these were classified according to the following codes: type of studies, research methods, population analysis and use cases, cognitive domains and learning theories, technological configurations. Finally, results from previous studies in terms of VR impact on learning has been considered.

3.1 Type of studies

The 68 empirical research works analyzed in this paper can be divided into two macro-categories: (1) papers describing the *development* of VR applications for educational purposes (i.e., 36 papers); (2) papers describing the *implementation* of VR applications for educational purposes and assessing their impact on learning (i.e., 32 papers) (Figure 4, left). Although distributed over the two decades considered, *development papers* mainly characterize the time span from 2005 to 2013, with just two previous papers in 2001. They then return in 2017, with a significant increase in 2019, but flanked by implementation papers. *Implementation papers*, although there are a few examples in 2009, 2012 and 2015, mainly spread from 2017 onwards with a steady growth leading to more implementation papers than development papers from 2020 (Figure 4, right).

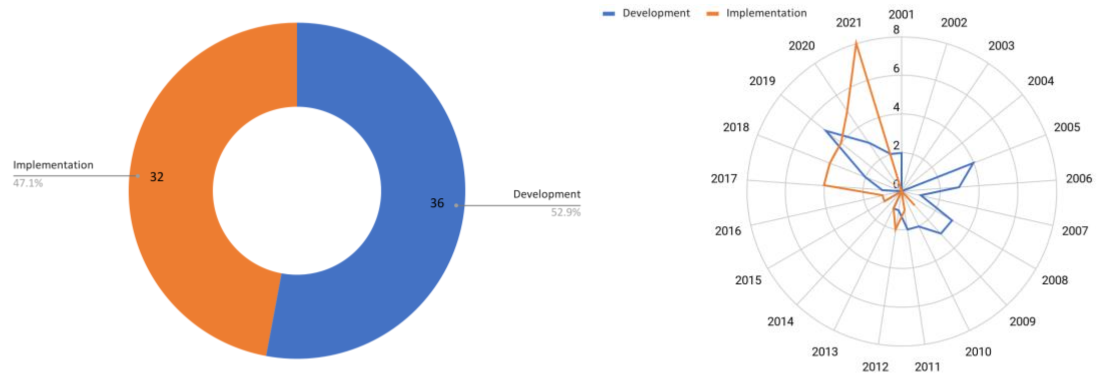


FIG. 4: Types of papers (left) and their distribution per year (right).

The *dependent variables* of implementation papers have been coded to highlight the main categories of factors driving the research about VR implementation for construction education. Most of the implementation papers (i.e., 19) focus on the impact of VR on learning. In some cases, this interest is made explicit in the goal to analyze the impact of VR in spatial visualisation (Ceylan, 2020; Bartosh and Anzalone, 2019), tacit knowledge acquisition (Wu et al., 2019a), knowledge transfer, knowledge retention (Eiris et al., 2021; Beh et al., 2021) as well as in allowing students to live a realistic experience (Sulbaran and Jones, 2012).

Another category of implementation papers aims to develop a VR application and to evaluate its effectiveness from a technological perspective, aiming to assess its usability and acceptance from the students. For example, Birt and Vasilevski (2021) compared the usability of single and multi-user mobile VR applications in construction education. Maghool et al. (2018) developed a VR environment to teach students about architectural detailing and construction processes with an in-game practice and assessment and through a pilot study they aimed to determine the usability and perceptions of the VR game. Newton and Lowe (2015) developed an immersive simulation game for teaching construction processes and it was evaluated for usability and perceived usefulness for teaching. Duckworth et al. (2012) developed a simulation game to teach students about excavation, but only usability was assessed. Nikolić et al. (2011) and Nikolić et al. (2009) developed an open source educational application and assess the usability of the system proposing a guideline for future developments of educational games.

The integration of VR in classroom and laboratory settings is also discussed in previous works (Lucas and Gajjar, 2021; Bartosh and Anzalone, 2019). Challenges have been revealed in designing effective learning processes and structure interaction if the solution does not provide the right level of usability for students, who can feel lost or confused moving within a VR environment (Peña and Ragan, 2017). The VR experience can also have different results based on the type of population involved in the interaction, proving to be more appropriate for some categories of students than for others (e.g., undergraduate vs graduate students) (Tan et al., 2017).

3.2 Research methods

Although in the case of development papers a research methodology is usually not specified (Figure 5, left), this is made explicit in the implementation papers that adopted quantitative, qualitative and mixed methods to test their dependent variables (Figure 5, right).

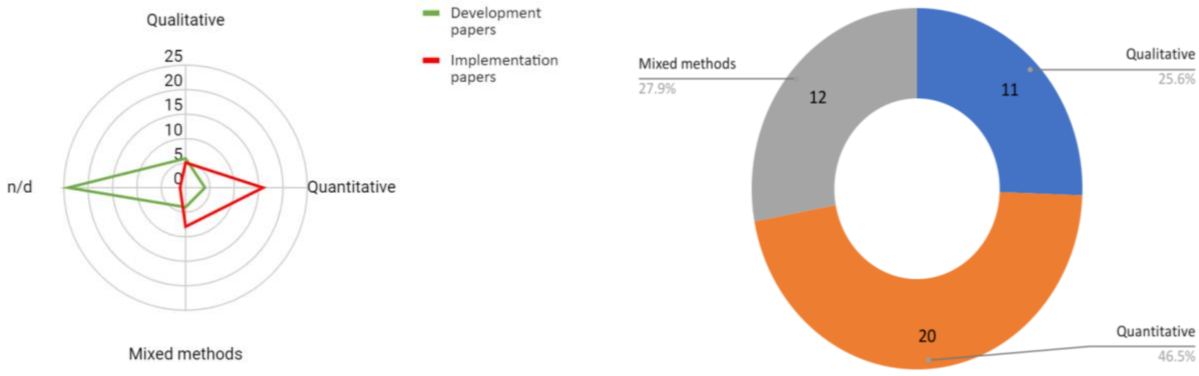


FIG. 5: Research methodology per type of paper (left) and research methods adopted in implementation papers (right).

Most implementation papers adopted quantitative research methodology to compare the learning impact of virtual reality tools against traditional and paper-based ones. On the other hand, only a few and temporally concentrated studies have adopted qualitative research methods. Mixed methodologies were adopted in a distributed manner throughout the time span considered (Figure 6). Moreover, while the majority of the reviewed studies used quantitative research methods, their sample sizes often appear to be rather small (Figure 6), limiting the extent to which the results can be generalizable, and instead remain predominantly descriptive. Only 27 out of 68 studies declared a sample size and only 9 studies out 68 have a sample size larger than 40 students, taking 40 participants with a 0.60 effect size as a cut-off point to run a statistical analysis (Kenny, 1987).

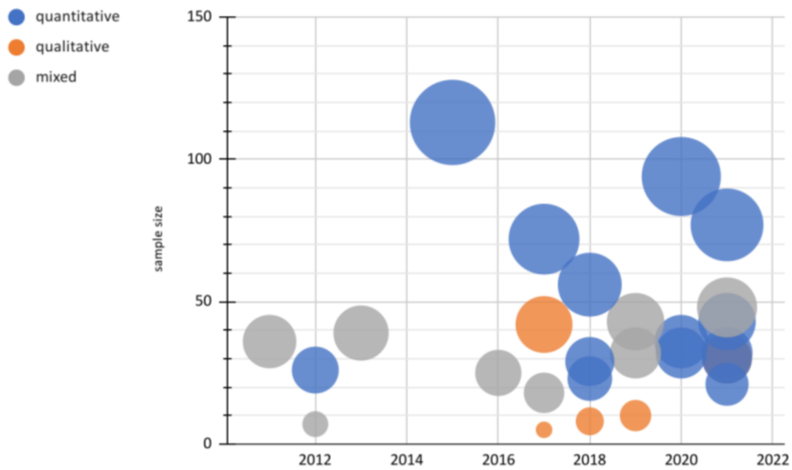


FIG. 6: Temporal distribution of research methods in implementation papers and related sample size.

3.3 Population analysis and use cases

From the analysis of the reviewed studies, it emerges that the implementation of virtual reality for educational purposes is mainly addressed to undergraduate students in construction-related curricula (Figure 7). 40 out of 68 papers involves construction students (59%) and 27 out of 68 studies (40%) declare to focus on undergraduate construction students. 10 out of 68 studies (15%) do not declare the population of students.

Moreover, the analysis of VR implementation revealed a wide range of educational use cases (Figure 8, left). Almost a third of the studies (21 papers out of 68) - development papers published between 2001 and 2011 - does not specify the use case VR is implemented for in construction education. The remaining 47 papers report use cases – especially from 2011 and 2021 (Figure 8, right) - that are mainly distributed in the fields of *design management* and *construction management*. Within the broad category of design management, the adoption of VR includes instances of supporting multidisciplinary design as well as the design review process in a collaborative setting. In construction management, VR is primarily used to visualize construction sequences (e.g., Lucas, 2020), to replace site visits with 360-degree views (e.g., Eiris et al., 2021), and to learn about principles of construction safety (e.g., Pedro et al., 2016). In teaching construction safety, studies typically compare how students perceive possible sources of risk between using VR and traditional, or paper-based representations. Fewer studies concern the use of VR for quantity surveying and for visualizing building components both for design and construction purposes.

FIG. 7: Population type and population sector.

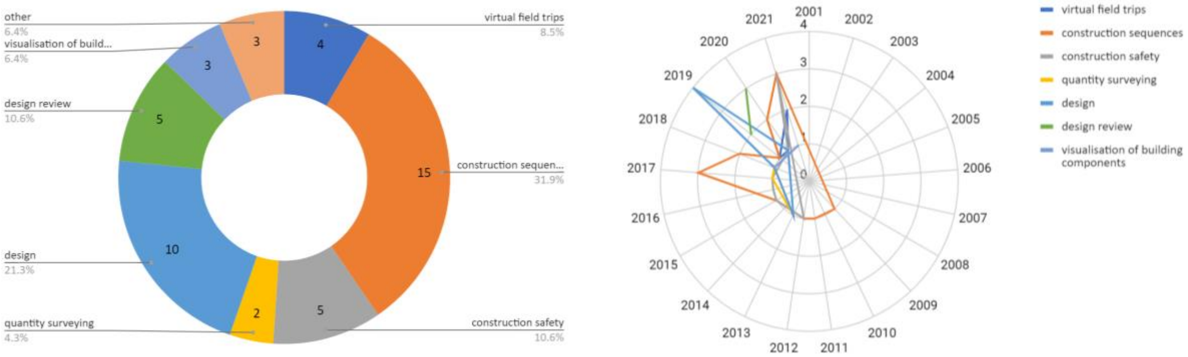


FIG. 8: Use cases for VR implementation in construction education (left) and their distribution per year (right).

3.4 Cognitive domains and learning theories

Almost all the reviewed studies (65 out of 68 papers) were found to have considered and included some of the cognitive domains and learning theories as a framework for developing and implementing VR in teaching. In terms of the cognitive domains, the papers were coded based on the six cognitive dimensions defined by the revised Bloom's Taxonomy (Krathwohl, 2002). The revised Bloom's Taxonomy categorized the possible cognitive processes that students might engage while learning into six domains, from simplest to most complex: *(1) understanding, (2) remembering, (3) applying, (4) analyzing, (5) evaluating,* and *(6) creating.* These domains based on difficulty can be further grouped into those of the lower domains (*understanding* and *remembering*), middle- (*applying* and *analyzing*), and higher domains (*evaluating* and *creating*). Typically, the revised Bloom's Taxonomy is used to formulate learning objectives of a pedagogical intervention or activity, such as those that have been defined for construction educational simulation games (Castronovo et al., 2018b; Castronovo et al., 2017b; Castronovo et al., 2014).

In the analysis, the papers were coded based on whether the authors stated the learning objectives of their intervention or the domains that they were assessing through their experiments. However, while most papers indicated a learning theory or cognitive domains, they fell short of specifying the learning objectives. Therefore, the studies without learning objectives had to be categorized based on the cognitive processes the authors aimed to engage students in or assess. A total of 194 codes were found, with 56 codes for *understanding,* 52 codes for *remembering,* 1 code for *applying,* 52 codes for *analyzing,* 25 codes for *evaluating,* and 8 codes for *creating*

(Figure 9, left). The majority of the codes were clustered for the publications within the period between 2017 and 2020. In particular, a growing number of studies during this period started to either develop interventions or assess learning that would engage in the *understanding, remembering,* or *evaluating* domains (Figure 9, right).

The analysis also looked at comparing the cognitive domains from the studies and the use cases that the students were asked to engage in. As it can be seen in Figure 10, the majority of the codes are related to the *remembering*, *understanding*, *analyzing*, and *evaluating* of design, and the *remembering* of construction sequencing. Design reviews is a use case that also has several *remembering*, *understanding*, and *analyzing*.

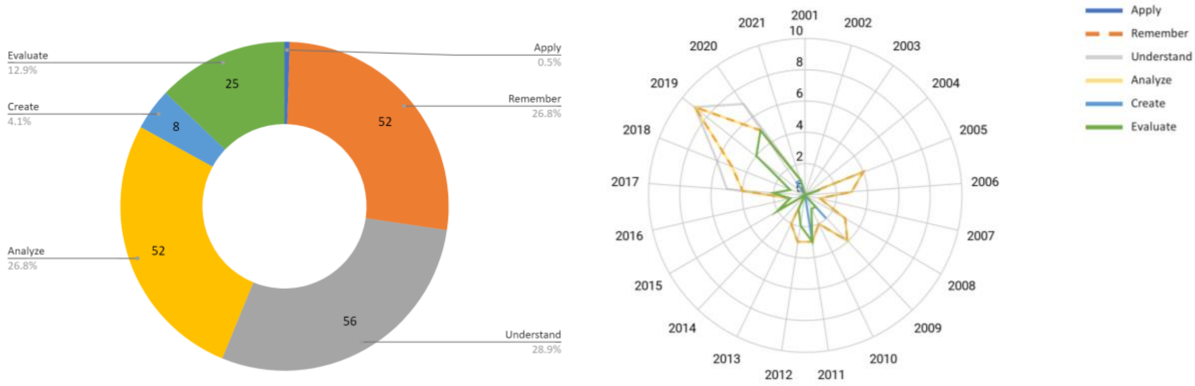


FIG. 9: Cognitive processes (left) and their distribution per year (right).

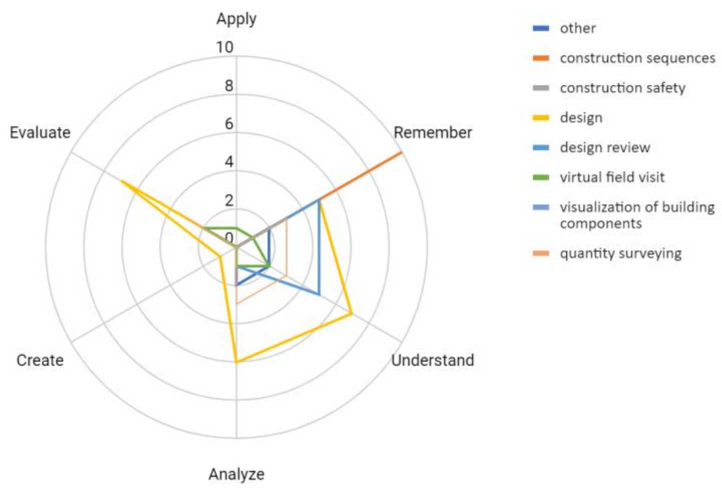


FIG. 10: Use cases and cognitive domains

Next, the learning theories included in the 68 papers have been evaluated. Learning theories define, describe, and explain the process that students and learners engage in while learning (Schunk, 2011). Some established theories and epistemologies include behaviorism (Pavlov and Gantt, 1928; Skinner, 1988; Watson and Kimble, 2017), social cognitive theory (Bandura, 1986), information processing theory (Schunk, 2011), constructivism and situated learning (Piaget, 1976; Vygotsky, 2012), and cognitive learning processes. These theories have been adapted to further explain the learning process, such as problem solving (Jonassen, 1997), active learning (Bonwell and Eison, 1991), learning-by-doing (Dewey, 1913), game-based learning (Gee, 2003) and multimedia learning theory (Moreno and Mayer, 1999). For example, cognitive learning processes can be used to describe the thinking skills that students need in order to solve problems (Schunk, 2011). Meanwhile, multimedia learning theory builds upon information processing to describe the learning process when students engage with different types of media, such as visual and auditory stimuli (Schunk, 2011). All of these theories are fundamental in performing research in learning, and any research in pedagogy should aim to align with these theories.

The analysis revealed that 30 out of 68 papers (44.11%) mentioned learning theories for a total of 43 codes. Most frequently cited learning theories include experiential learning (11), problem solving (6), active learning and learning-by-doing (3), while other theories were mentioned once or twice (Figure 11, top). Moreover, after 2017 there has been a growing alignment of studies with learning theories, with 36 out of 43 (83.72%) code mentions (Figure 11, bottom).

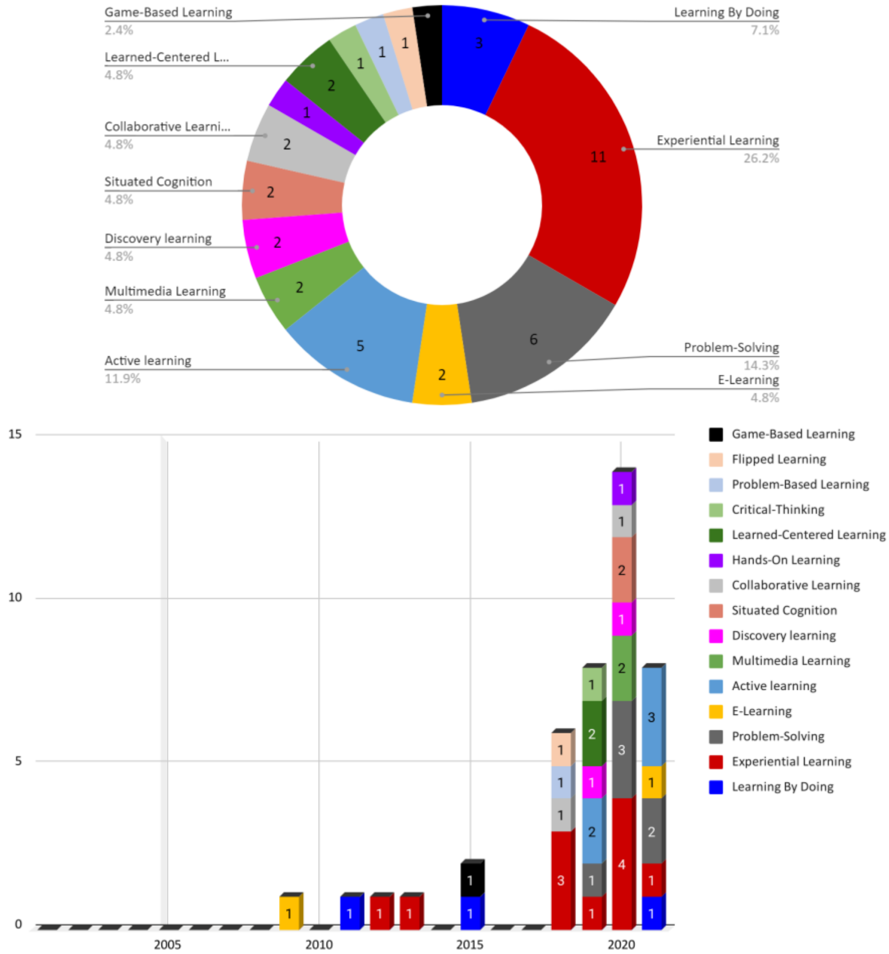


FIG. 11: Learning theories and concepts used in the reviewed studies (top) and their distribution per year (bottom).

3.5 Technological configuration: level of immersion, VR content and mode of interaction

One of the important aspects in understanding any claims made about the effectiveness of VR in construction education is discerning the technology configurations, such as input and output devices, level of immersion, or types of interactions, as well as the characteristics of content representations, whether they are static or dynamic, realistic or abstract. The level of visual immersion is one of the main parameters used to classify the VR technologies into fully-immersive systems, which entirely cover the user's field of view (e.g., head-mounted displays); semi-immersive systems, which partially cover the user's field of view (e.g., large screens), and non-immersive systems (e.g., desktop monitors).

Figure 12 (left) provides an overview of the VR configurations adopted in the reviewed studies, where the majority has been almost evenly divided between non-immersive or fully-immersive technologies. Semi-immersive technologies, such as room-like or multi-screen VR, have been implemented only in 6 of the reviewed studies, largely coinciding with the earlier studies from the 2000s. The non-immersive configurations appear to be the prevalent type of VR adopted between 2008 and 2012. The use of fully-immersive virtual reality configurations sharply rises from 2015 to become dominant in 2017 and further growing until 2021 (Figure 12, right).

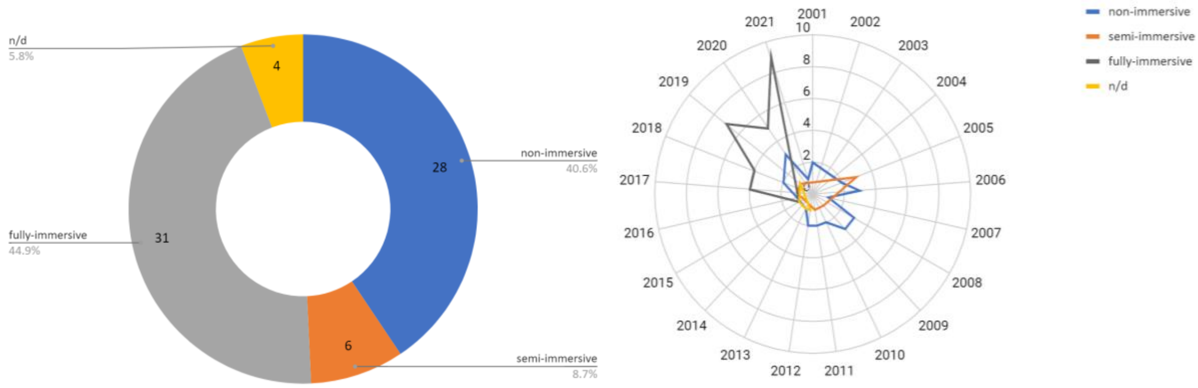


FIG. 12: VR configurations used in construction education based on level of immersion (left) and their distribution per year (right).

Regarding the VR content representation, it is interesting to evaluate its development over time (Figure 13). 3D models prevail as the type of content with which students interact in a virtual reality environment. While they continue to be the main source of content for VR, the terminology shifts in recent years to models being increasingly declared as BIM models, which are mentioned for the first time as such in 2018. The source of 3D model development has also evolved over time: first models were produced in AutoCAD 3D and then increasingly surpassed with those developed in SketchUp, Revit, or Rhyno. These models have also been increasingly created with game engines such as Unity3D and Unreal to provide for more custom user interactions within the virtual environment.

Educational simulation games, which incorporate the interactive and pedagogical aspects with 3D models, represent another important content for the adoption of VR in construction education. Mentioned for the first time in 2009, they continue, as evidenced by publications in 2020, to be used as tools able to increase students' performance and involve them in learning activities. Between 2011 and 2015, some courses also adopted virtual worlds such as Second Life (e.g., Ku and Mahabaleshwarkar, 2011) to simulate, through an avatar, an experience in the construction sector. Study by Sulbaran and Jones (2012), for example, adopted Second Life as a virtual platform to create a socially interactive role-play experience for students to learn about construction site safety, construction sequences and resource management. Recently, since 2019, content such as 360-degree images or time lapse videos have been used to reconstruct and allow students to visit a construction site, albeit in a virtual environment.

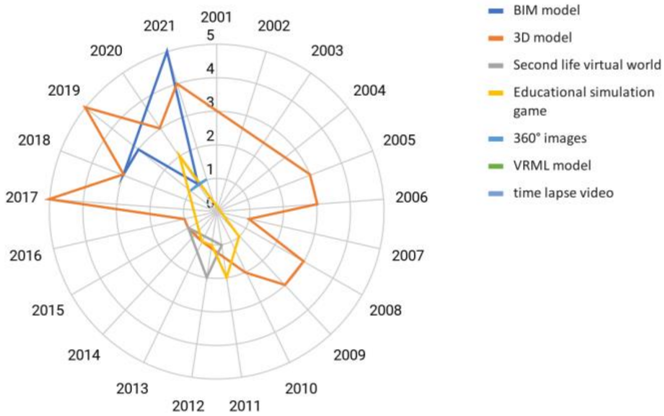


FIG. 13: VR content.

Moreover, VR "could engage not only the user's vision but also the sound, haptic (touch), smell and taste with computer interfaces that encompass often real-time interaction" (Kassem et al., 2017). However, the literature review reveals a very limited application of multi-modal VR implementation for construction education. Though examples of haptic VR for training use cases exist (e.g., Gallegos Nieto et al., 2017; Hilfert and König, 2016; Abidi et al., 2015), visual modality alone dominates across the 68 studies. Audio-based interaction is included in 6 studies as a way to recreate a realistic job-site experience in virtual field visits, for the analysis of construction sequences, or to engage and motivate students by means of a virtual inspector that provides them instructions to proceed (Eiris et al., 2021; Beh et al., 2021; Try et al., 2021; Wang et al., 2020). In one instance, audio has been used for acoustic feedback in the application of VR for architectural design (Bartosh and Anzalone, 2019). In Şahbaz (2021) students receive audio information when selecting an object in the virtual environment as a way to improve the learning experience in architectural education.

3.6 Results from previous studies in terms of VR impact on learning

The implementation of virtual reality in construction education has mainly focused on discerning the possible benefits for teaching and learning compared to traditional and paper-based methods. Şahbaz (2021) developed an interactive simulation compatible with both desktop interfaces and the most common fully-immersive VR equipment for students to learn about basic construction elements, replacing real construction site visits. Şahbaz (2021) claimed to have achieved an improvement in students' learning, who applied a sample curtain wall system from start to finish by trial and error, if compared to traditional methods. Lucas and Gajjar (2021) developed and implemented a desktop-based and game-scoring virtual environment to have a better understanding in construction sequences. These studies claimed that VR-based learning has higher system usability in terms of visual output and knowledge retention than paper-based learning.

Motivational and engagement factors of a prototype immersive learning environment are also recognized in Beh et al. (2021), who asked students to navigate through the VR environment in the first person by using a VR headset and a multiple-choice assessment was used to achieve learning outcomes in the domain of building utility inspection. Mastli and Zhang (2017) explored the use of construction simulation in facilitating students' understanding of construction processes and highlighted how, based on data collected, such simulation helps students to plan construction. Pedro et al. (2016) aimed to engage students and provide practical experience in construction safety by proposing a novel approach integrating a hazard identification game with traditional construction materials. Interim results indicated that the system offers a medium for experientially improving hazard identification ability, transferring safety knowledge and engaging students.

Moreover, results from the reviewed studies also show a slight increase in understanding of space and other features of the model when using VR as opposed to looking at rendered images that represent traditional learning materials. Vassigh et al. (2020) adopted VR to let students experience building spaces by walking through them in a non-immersive set up created in Unity3D. Based on this experience, Vassigh et al. (2020) noticed higher success on students' understanding as well as on their attitudes towards collaborative learning if VR is adopted. Ceylan (2020) presents a comparative study on the use of VR technologies in the first year of architectural education to improve the visual and spatial recognition skills of students. Ceylan (2020) claimed how VR technology could be beneficial in various aspects like the perception of certain physical characteristics of a model but also in students' enthusiasm to participate in the design studio courses. On the other hand, Sopher et al. (2019) has not found any definitive differences between the studio space and the immersive virtual environment in supporting design development. Rather, immersive learning spaces were shown to support design convergence, considered to be an essential skill. Abdelhameed (2013) adopted VR to allow students to explore and propose a structural system during the architectural design process. VR resulted to be an effective design medium for visualizing structural systems and have an immediate evaluation. Moreover, VR helped students to visualize and understand the system before going back to the modeling applications to make design modifications.

Visualization, understanding and spatial cognition skills have been further discussed by Eiris et al. (2021), who adopted 360-degree panoramic site visits to deliver contextualized learning and they noticed how students performed better using VR for site observation but no difference from traditional methods was found for activities requiring abstract knowledge of site elements. Moreover, participants with higher spatial visualization abilities performed better in both the learning environments, the traditional classroom and the VR-enabled conditions.

Kandi et al. (2020a) investigated the impact of a fully-immersive virtual reality game in a classroom environment on how students identify design mistakes during the design review process and the development of their design review skills. The results demonstrated that the educational simulation game helped students to identify a higher number of design mistakes compared to doing the same task with a paper-based documentation. Working on the same topic and extending it, Kandi et al. (2020b) analyzed the order in which students accessed the information and they demonstrated how students that played the game after performing 2D drawing reviews scored significantly higher in the knowledge test. Based on their results, the game could be therefore implemented in an integrated manner with traditional representation.

Additional studies suggested how VR could be integrated with other learning tools and documents. Elgewely et al. (2021), for example, looked at the potential introduction of head-mounted displays into a construction classroom to explore the 3D model of a building in the construction phase. On the one hand, they considered VR as an effective and motivating educational medium that can enhance the students' learning experience and learning outcomes compared to traditional paper-based studying. On the other hand, they also highlighted the logistical challenges of consistently implementing the VR environment in regular classes. Bartosh and Anzalone (2019) described the incorporation of VR as a tool in various classroom and laboratory settings, recognizing the educational outcomes of this incorporation. However, the authors propose that simulation and analysis cannot replace experience in the act of architectural design in academia, practice and research. Tan et al. (2017) compared the perception between graduate and undergraduate students on the adequacy of the VR experience to understand construction methods and it was found that spatial detailing in VR can be useful for complementing lecture notes. Wang et al. (2018) also analyzed the development status of VR and its application in teaching and learning. According to them current VR technology can only be used as an auxiliary means in construction education.

3.6.1 Emergent themes

Some themes were identified in the literature that had not initially been nominated for examination. If most of the studies sought to test the effectiveness of VR by comparing VR-enabled and paper-based learning content, fewer studies also investigated other factors related to VR implementation in construction education. For example, Wu et al. (2019b) investigated whether the impact of virtual reality on learning changes between novices and experts, considering how it might facilitate tacit knowledge acquisition and expertise development. They focused on the design review use case and their results revealed highly comparable patterns of behaviors and demonstrated that there were no statistically significant differences in design review and assessment outcomes between novices and experts in the VR-constructed virtual environments, despite novices' apparent lack of professional experience and expertise. Other studies have recently analyzed how virtual reality could meet the need for e-learning and online education because, for example, of the Covid-19 contingency (Sanchez et al., 2021; Try et al., 2021).

Moreover, Nikolić and Windess (2019) evaluated different VR configurations for construction education. They analyzed differences between types of VR based on their immersive experience, exploring a pedagogical value of using immersive instead of desktop-based VR to teach construction students how to identify and evaluate the spatial characteristics of their design in terms of sizes, layout or structural issues. The study demonstrated how students using immersive VR perform slightly better compared to those using the monitor. Nikolić and Windess (2019) also revealed further multi-dimensionality of VR and inherent complexities in how the domain knowledge, novelty effect, content and perceptual differences may influence the spatial understanding and over performance. According to Nikolić and Windess (2019), in fact, observation of students' interactions with the model while completing the tasks suggest a greater complexity in how the navigation patterns, knowledge domain and technological experience may be affecting the way they perceive the design.

3.6.2 The role of VR technologies

According to the retrieved studies, VR technologies may influence the potential impact of virtual interactions on learning because of some limitations. For example, it emerges that significant time and resource investments are needed in order to get an impact on learning by using VR (Eiris et al., 2021). VR implementation, in fact, requires longer learning time and higher performance scores (i.e., effectiveness) are not guaranteed (Beh et al., 2021). Another limitation is related to the availability of VR technologies. For example, because of the shortage of HMD availability in educational contexts, desktop-based solutions are preferred in some cases (Lucas and Gajjar, 2021) and some technologies initially adopted in research studies are now (Birt and Vasilevski, 2021).

Moreover, VR interaction functionalities do not completely imitate actual interactions, which still lacked realism (Try et al., 2021). In some cases, navigational affordances which allow teleporting or fly through are adopted in addition to walking (Nikolić and Windess, 2019). Furthermore, cybersickness and user comfort might reduce the usability of the system (Eiris et al., 2021; Lucas, 2018). Finally, offline single-user applications limit the ability to produce a sense of teamwork as well as reduce the communication opportunities between the learners. For example, Birt and Vasilevski (2021) discussed how when participants move from single-user VR to multi-user VR, this significantly increased the overall perceived usability and learning experience.

4. DISCUSSION OF THE RESULTS

Contextual factors and trends in VR implementation for construction education have been identified. They are discussed in relation to three main foundations: (1) educational theoretical foundations, (2) methodological foundations and (3) technological foundations.

4.1 Educational theoretical foundations

The results from the critical review have provided an insight into the current efforts of the implementation of virtual reality into pedagogy. In particular, it has provided a timeline of how such implementation has changed throughout the last twenty years. Starting with the learning theories, the trend illustrates that research rarely accounts for educational learning theories as a foundation to conduct studies, as only 30 papers out of 68 (about 44.1%) have underpinned their studies with established learning theories. However, based on the results, since 2017 there has been a growing trend of researchers leveraging learning theories as foundations for their studies. The most common learning theory that is used as a foundation for research is experiential learning based on Kolb (1984), with 11 papers citing it. Similarly, there are learning theories such as problem-solving (Jonassen, 1997), active learning (Bonwell and Eison, 1991), and learning-by-doing (Dewey, 1913), that have been leveraged by several researchers. While several of these learning theories do provide a framework for how students are going to engage with a learning environment, they were not developed to be theoretical frameworks for computer-based or virtual reality-based education. However, these learning theories can be leveraged in conjunction with and supported by game-based learning (Gee, 2003) and multimedia learning theory (Moreno and Mayer, 1999). Moreover, multimedia learning theory is only cited in 3 papers in the last three years, and game-based learning theory was only cited once. Multimedia learning theory was cited only once by Manton et al. (2005), while it was leveraged together with problem-solving learning theories by Kandi et al. (2020b) and Walker et al. (2019). Based on these results, it is clear that research in the application of VR in construction education needs to be further underpinned and aligned with learning theories as they can support and strengthen the methodological rigor of the studies and the generalization of the contribution of results.

Similar to learning theories, since 2017 researchers have increased their assessment focus of cognitive domains. The retrieved papers have been analyzed based on the revised Bloom's Taxonomy proposed by Krathwohl (2002), evaluating the learning objectives, when stated, and the cognitive processes that each study was aiming to engage students in or assess. Based on the analysis, the majority of the research, 55.7% of all papers, has focused on lower-order cognitive domains and skills, such as *remembering* and *understanding*. Meanwhile, 27.3% of the studies focused on middle order cognitive domains and skills, such as *applying* and *analyzing*, and only 17% focused on higher order cognitive domains and skills, such as *evaluating* and *creating*. The low focus on assessing and engaging students in middle and higher order domains and skills could be due to challenges in developing VR experiences and environment to elicit such cognitive processes. This finding is interesting as very few studies have investigated the impact of VR on higher order cognitive domains since 2017, while there has been a larger increase in investigating lower order cognitive domains since 2017. This could be due to the lower cost and, therefore, popularization and commercialization of VR headsets. However, one would expect that with technology becoming more available, the analysis of higher order cognitive domains would also increase. Therefore, there is still the need to investigate the impact that VR has on middle and higher order cognitive domains.

When looking at the different use cases and cognitive domains it is worth noting that the majority of the use cases focus on the evaluation, understanding, and analysis of design, remembering of construction sequences, and remembering and understanding design review. Therefore, here another research opportunity could be identified to grow the amount of use cases that can elicit the *creating* and *applying* domains. In parallel with the use cases and cognitive domains, the results show that the dependent variables category *VR impact on learning* being measured have focused mainly on tacit knowledge acquisition, knowledge transfer, and knowledge retention, which are mainly lower order cognitive processes. On the other hand, only 24 out of the analyzed 68 studies (about 35.3%) have looked at measuring impact on learning.

Based on these results there is a clear need to increase the number of studies that assess and measure the impact that VR has on learning. Furthermore, future researchers need to also go beyond lower order cognitive processes and to assess skills that students will need in the industry. This discussion on educational theoretical foundations has shown that researchers need to strongly align their theoretical foundations with their methodology and assessment.

4.2 Methodological foundations

In addition to providing a vision of the current educational theoretical foundations of current literature in the application of VR in construction pedagogy, the results of this study provide a unique perspective of the methodologies deployed in this research topic. Starting with the *type of studies* presented in the selected literature, only 47.1% of the papers focused on the implementation and assessment of VR in learning environments. In comparison, the remaining 52.9% of the papers focused on presenting the development of VR environments and applications. Furthermore, when looking at the publication frequency per year for these two types of studies, before 2017, there had been only 7 implementation studies (22%) and 25 studies (78%) after 2017 (Figure 5, right). This result indicates that 78% of the implementation studies happened in the last four years. Meanwhile, the opposite is observed for development studies, with 23 (64%) studies before 2017 and 13 (36%) after 2017. Similar to the results in the previous section, the growing frequency of implementation studies past 2016 could be attributed to the commercialization and lower cost of virtual reality hardware, such as the Oculus Rift. Additionally, these results illustrate the need to continue assessing the impact of VR implementation in pedagogy. In particular, the results demonstrate that construction academics need to perform further research before the benefits that VR has in construction education can be validated, generalized, and advocated for.

Moreover, there are variations in how consistent approaches are among the studies analyzed in this literature review. In fact, methodological and pedagogical challenges limit the extent of claims the reviewed studies make about VR effectiveness. What emerges from the analysis of the retrieved papers is that often both the research methods and the rationale are unclear, with no clear learning processes defined. The type of learning approach and its correlation with VR implementation is not discussed, as well as the effect from the order of the learning approaches is not observed except in Kandi et al. (2020b). In addition, the applications described in the retrieved papers are often under development and interim results are usually discussed, not providing a full-scale implementation to assess learning. Validated assessment instruments are not adopted and in most cases sample size is not sufficient to generalize findings, which result to be not statistically significant and purely descriptive. Only 27 out of 68 (40%) studies, in fact, declared a sample size. In particular, a majority of the quantitative and mixed methods studies have small sample sizes, with only 9 studies out 68 or having a sample size larger than 40 students - taking 40 participants with a 0.60 effect size as a cut-off point to run a statistical analysis (Kenny, 1986).

Furthermore, samples are usually related to a single subject and a narrow age band with self-reported information about the population involved. From the *population* results, it is clear that the majority of the studies have focused on the impact that VR has on undergraduate construction students, showing that further research could rather focus on architecture and mixed disciplines (e.g., architectural engineer and built environment) pedagogy. In addition, the impact of VR on learning is not actually validated because the performance of learners using VR is not always measured; when it is measured subjective self-reported measures are usually used. Learning assessment, in fact, relies on students' perceptions and opinions and details on the testing and evaluation process are not reported.

Finally, the terminology around VR in construction education is loose, where some studies conceptualized VR as interactive virtual worlds without any regard on the display and interaction technologies (e.g., virtual worlds, simulation games displayed on monitors) whereas others specifically focused on exploring the immersive spatial understanding.

In general, these results illustrate that there is a growing need to perform additional research to validate the role that VR has in construction education. When looking at the validation framework for simulation by Feinstein and Cannon (2002), researchers must evaluate both the internal and external validity of a simulation before it can be considered "educationally valid". Therefore, the process of validation requires the assessment of an educational simulation through multiple studies and using a variety of research methodologies. Researchers could run quantitative experiments with large sample sizes that assess students' learning to address the Feinstein and

Cannon's (2002) framework's external educational validity. Meanwhile, researchers could run qualitative experiments, such as verbal protocols, with smaller sample sizes, to address Feinstein and Cannon's (2002) framework's internal educational validity and assess if students engage with simulations with insight. This discussion on methodological foundations has shown that researchers need to design and adopt rigorous research methodologies to grow the validity of VR implementation in construction education.

4.3 Technological foundations

While there is an evident uptake of theoretical frameworks to support the development and implementation of VR in recent years, claims about the VR effectiveness in construction education also depend on discerning the technology configurations and characteristics of both the representation content and the presentation medium. Regarding the content characteristics, most studies generally report the use of 3D models, or more frequently as BIM models in recent years. Thus, dominated by applications in design and construction practice, VR representations most often include realistic 3D models for navigation, exploration, and review tasks. In some educational simulation instances, the content may offer users more interactive and dynamic ways to modify or build components, test construction processes with real time feedback, or manage resources. Here, experiencing visualizations is inseparable from technology media in which users view information on various displays or interact with using input devices. The medium in this instance has a primary goal to render itself invisible to the user and focus attention on the information. What makes VR a powerful and engaging platform is its ability to encourage students to interact with information in novel ways. Although VR tends to be primarily seen through the lens of visual displays, interaction as one of the defining characteristics of user experience in VR (Sherman and Craig, 2003) is defined through the combination of input and output devices. Examples from the gaming industry demonstrate rapid developments in interactive capabilities with tracked controllers, which can assume the appearance of any tool, such as markup, drawing, object manipulation or navigation tools. Thus, the view of users experiencing VR models through custom interfaces and combinations of input and output devices frames VR as a multifaceted and flexible approach to visualizing and interacting with information (Nikolić and Whyte, 2021). For this reason, the efficacy of VR is highly contextual and tailored to user needs, where the choices regarding information content and perceptual characteristics of the system largely depend on the nature of the tasks, user experience sought, and outcomes.

The majority of observed VR applications in construction education primarily rely on the visual, whereas the use of haptics, sound and particularly smell remain largely underexplored. VR experiences are dominated by the visual sense and thus, display configuration is the primary consideration when it comes to choosing between non-immersive (screen- or projection-based) configurations and fully immersive systems, such as HMD solutions. The review of studies revealed that the largest proportion of VR implementations in construction education have used non-immersive configurations such as desktop monitors, until 2016 where we observe a sharp rise in the use of fully immersive single-user VR, such as head-mounted displays. This increase in the use of HMDs may coincide with the proliferation of relatively affordable consumer market products such as OculusRift, Samsung Gear VR or HTC Vive with continually improved performance. Large display configurations, such as semi-immersive VR projected screens remain scarce, possibly as they are often custom designed and require more space. The issues of costs, space, setup complexity, operation or availability may perhaps be the dominant considerations for using lower-cost VR solutions in education, rather than the considerations for how appropriate such configurations are from the perspective of user tasks, goals and user characteristics. For example, HMD is by default a single user-tracked experience with stereoscopic viewing tailored to support first-person view and interaction with a virtual environment, and as such is well-placed for tasks that require users to evaluate spatial information or elicit emotional responses. At the same time, these attributes may not be desirable in large group, or collaborative settings as they may inhibit social interactions, interfere with the dialogue, and affect collaboration (Maceachren et al., 2005). One aspect of HMD configuration, though, that differentiates it from non-immersive or projection-based VR, is the sense of disembodiment due to the user’s inability to see own body in a virtual world, which can further invoke a sense of discomfort or motion sickness. Thus, due to their distinctive features, VR applications may not offer the most effective experience in all cases.

The reviewed studies do not necessarily define the nature of the learning task nor specify the types of user experiences as a way to justify the choice of one VR system over the other. Though studies in human-computer interaction and visual science offer heuristics that can help primarily technology developers envision and understand user, information and system requirements, for educators this may be a challenging task as it also requires knowledge of perceptual, cognitive, as well as technological considerations. This implies that in an educational context, educators may simply need to work with what is available and affordable. Nevertheless, it is generally recognized that the knowledge of what constitutes effective visualizations often lags behind rapid technological development (Orland et al., 2001).

5. CONCLUSIONS

The implementation of virtual reality attracts considerable attention from both construction industry and academia due to the potential that virtual prototyping has in terms of engaging stakeholders in an intuitive and interactive way. In construction education, VR-based learning is investigated because of the impact it might have on knowledge retention as well as for the motivational and engagement factors that it could provide, especially when compared to traditional and paper-based learning.

This paper undertakes an extensive literature review regarding the implementation of virtual reality in construction education. The content-analysis methodology has been applied to the review of 68 journal articles and conference proceedings published from 2000 to 2021, aiming to depict the research development in this domain. The annual number of relevant publications indicates a growing research interest in this topic. In particular, the paper describes the transition of the international research from *development papers*, focused on the development of VR environments, to *implementation papers*, focused on the assessment of VR impact on learning.

By a content analysis of the previous research works, three pillars have been identified as key research themes to be discussed: (1) educational theoretical foundations as well as (2) methodological and (3) technological ones. Based on results from the review, it is clear that research in the application of VR in construction education needs to be further underpinned and aligned with learning theories and there is the need to increase the number of studies that assess and measure dependent variables related to the impact that VR has on learning. Future researchers need to also measure and assess skills that students will need in the industry as well as to strongly align theoretical foundations with methodology and assessment. Moreover, this study provides a unique perspective of the methodologies deployed in this research topic and what emerges from the analysis of the retrieved papers is that both the methods and the rationale are often unclear. Results illustrate that there is a growing need to perform additional research to validate the role that VR has in construction education and researchers have to design and adopt rigorous research methodologies to grow the validity of VR implementation in construction education. In addition, it has been noticed how, due to their distinctive features, VR applications may not offer the most effective experience in all cases and the reviewed studies do not necessarily justify the choice of one VR system over the other in terms of learning task and user experience.

Furthermore, this study differs from previous review papers about VR implementation in construction education because it integrates the individual findings from previous reviews by adding additional perspectives such as the impact of virtual reality adoption on learning processes and theories. Results from the literature review have provided an insight into the current efforts of the implementation of virtual reality into pedagogy. In particular, it has provided a timeline of how such implementation has changed throughout the last twenty years. In addition, this study provides a unique perspective of the methodologies deployed in this research topic as well as an overview of the technological configurations adopted for VR use cases in the construction education domain.

At the same time, the review has some limitations in the light of the methods used. The retrieval process, for example, which is based on a desktop search through a selection of literature search keywords, may not guarantee a comprehensive coverage of the papers that are worth reviewing. However, such an approach suffices for providing a considerable amount of significant research works from which the study could generalize findings and recommend future directions.

Finally, this extensive review of studies dealing with the implementation of virtual reality in construction education is of significant value to scholars in providing them an overall picture of previous research efforts and in illustrating a future research roadmap for this field.

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