A Scoping Review of Immersive Virtual Reality in STEM Education

Nikolaos Pellas, Andreas Dengel, and Athanasios Christopoulos

Abstract—**Although virtual reality (VR) simulation training has gained prominence, review studies to inform instructors and educators on the use of this technology in science, technology, engineering, and mathematics (STEM) are still scarce. This article presents various VR-supported instructional design practices in K-12 (primary and secondary) and higher education in terms of participants' characteristics, methodological features, and pedagogical uses in alignment with applications, technological equipment, and instructional design strategies. During the selection and screening process, 41 ($n = 41$) studies published in the period 2009–2019 were included for a detailed analysis and synthesis. This article's results indicate that many studies were focused on the description and evaluation of the appropriateness or the effectiveness of applied teaching practices with VR support. Several studies pointed out improvements in learning outcomes or achievements, positive perspectives on user experience, and perceived usability. Nevertheless, fewer studies were conducted to measure students' learning performance. The current scoping review aims to encourage instructional designers to develop innovative VR applications or integrate existing approaches in their teaching procedures. It will also inform researchers to conduct further research for an in-depth understanding of the educational benefits of immersive-VR applications in STEM fields.**

Index Terms—**Computer-aided instruction, educational technology, engineering, mathematics (STEM), science, student experiments, technology, and virtual reality (VR).**

I. Introduction

SCIENCE, technology, engineering, and mathematics (STEM) education is growing rapidly in many countries around the world as the new statistical data show [1]. Knowledge acquisition in many STEM fields requires students' learning experience within well-designed instructional approaches that should provide experimental (hands on) practices and tasks with high representational fidelity and realism in simulation [2].

However, many instructional designers and educators face several difficulties when applying laboratory experiments and practice-based tasks to a wide range of fields from primary and secondary (K-12) until higher education (HE). The most frequently referred is ranging from the complex transportation of students to a location with several laboratories to a variety of experiments that might be too dangerous or expensive. Also, access to real sources is sometimes time-consuming, and the lack of support from the instructor(s) or the administrative staff can usually cause students' frustration and dissatisfaction [3].

Technological advances in the field of virtual reality (VR) have been progressed by using various methods and computing systems for the projection, interaction, and multimodal manipulation of visual elements. There has been an increasing effort to fully understand the technical background of VR in pursuit of developing effective applications, depending on the type of the systems or the platforms, which can support such efforts [4]. Unlike the most well-known nonimmersive-VR technologies, such as "social" virtual worlds (VWs), e.g., second life (SL) or "open source," e.g., OpenSimulator, which are displayed on a computer monitor, immersive VR provides different perspectives. All users have their virtual representation into VWs called "avatar" to interact and communicate (a-)synchronously with other (or not) peers using a keyboard, a mouse, and a broadband Internet connection [2]. Immersive VR allows each user to be immersed in a digital environment generated by a computing system, giving the impression of realness, spatial presence, and engagement in a first-person form. Thus, the "sense of presence" exists when the user's experience with the feeling of "being there" and the view of changes in objects' motion can lead to greater perception and subjective sense of immersion into a simulated environment [5].

In contrast to VWs, immersive-VR systems provide sensory feedback to users based on their physical position, which is mainly achieved by tracking motion computing devices. The consequences of such actions and outcomes are projected in a digital environment, where each user exclusively interacts, and the computing system responds to every action that is made. VR provides multisensory interaction using the following four components: optical, acoustic, kinematic, and tactile, giving unprecedented opportunities to extend user experience in teaching and learning [6], [7]. Moreover, the application designers and developers who want to integrate VR technology in the classroom need to understand how to use the VR technology's basic concepts, such as "presence" or "immersion." VR concepts and applications are provided by utilizing computing resources to generate digital elements with realistic simulated representational fidelity to visualize specific contexts in which practice-based tasks can take place. The four most essential technologies that can provide different

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ways of interaction and immersion with computing systems are as follows:

1) desktop-based, such as room-sized displays to project 3-D content, e.g., *cave automatic virtual environment* (CAVE) [4];
2) head-mounted display (HMD) devices, such as Oculus Rift or HTC Vive [8];
3) mobile VR, such as Samsung Gear VR or google cardboard [9];
4) wearable spherical video-based VR [10].

Among such devices, an interactive and immersive 3-D user interface (UI) is provided on a display device combined with control mechanisms. In desktop-based VR applications, content is displayed by computer monitors, and the control mechanisms are executed by using a keyboard and a mouse for rich interaction. In HMD-based intuitive VR systems, content is displayed by headsets with a small display optic in front of each eye, and interaction is achieved by using handheld controllers.

During the past decade, a growing number of studies related to STEM fields have been published. A total of ten studies utilized VR in K-12 fields, including science [6], [11]–[13], technology [9], [14], mathematics [15]–[21], and engineering [19]. Additionally, a total of 31 studies applied several learning tasks using various VR applications in different HE disciplines that encompass science [20]–[34], technology [10], [35]–[40], and engineering [8], [41]–[48].

VR can support several applications of virtual laboratories, "hands on" experiences, and practical training to foster students' performance or learning outcomes/achievements. Within VR-supported instructional contexts, students can explore learning materials (e.g., [13], [18]) and construct meaningful prototypes or simulations without considering the spatial-temporal restrictions for auditory and visual integration (e.g., [9], [21]). Such tasks can improve users' experience in practice-based professional learning deriving from the consequences of their actions in real time that are provided visually and acoustically (e.g., [6], [8]).

Several literature reviews were conducted during the past decade focusing on the use of VR in K-12 and HE settings. For instance, Merchant *et al.* [7] conducted a meta-analysis of 67 studies to understand the educational use of desktop-based VR technologies as an assessment, diagnostic, or therapeutic tools. Nonetheless, the same authors have not recommended any tools or instructional design contexts in which VR can be applied sufficiently. Jensen and Konradsen [49] aggregated 21 studies published in the period 2013–2017. The same authors reviewed the use of HMDs in education and training for skill acquisition by examining factors influencing immersion and presence for applying VR in education. While Jensen and Konradsen [49] found situations that HMDs are useful for cognitive, psychomotor, and affective skills acquisition, they did not suggest any appropriate content development and the design elements that could facilitate the educational process contrary to a more entertainment-oriented one. Wang *et al.* [50] provided evidence on the use of VR applications for future directions exclusively in engineering education and training by analyzing 66 studies published in the period 1997–2017. Nevertheless, the same authors did not analyze how VR applications are associated with the content, design elements, or learning theories.

Although the above reviews have provided important aspects and considerations on the use of VR in education, there was no categorization identified by reviewing previous studies regarding the instructional design contexts using the HMD and desktop-based VR devices in STEM. As VR applications have gained significant ground, it is of great importance to identify any missing studies analyzing and presenting the potential benefits of using this technology with several computing devices. To fill this research "gap," this article offers a review aggregating a significant number of studies focusing on the impact and potentials of VR in different learning fields. Hence, there is a reasonable need to conduct a scoping review of previous studies to critically considering students' experience, outcomes, and performance within specific instructional contexts supported by VR in STEM fields.

This scoping review aims to outline a research area that is associated with the impact of VR in STEM instructional design contexts. The authors gathered and synthesized results from previous studies to identify any recent trends and research "gaps" during the past decade. The purpose is to examine broadly the relevant literature about VR uses in terms of the applications, methodological features, visual elements, characteristics, and any possible associations among these domains. It also investigates STEM fields in K-12 and HE settings to understand better how VR has been recently applied by highlighting the importance of designing effortful practices and applications. The current review adds to the literature by conveying information on the potential use of VR aligned with teaching models and/or theoretical frameworks to advise instructors and educators considering the impact of this technology in teaching and learning.

The structure of this article is as follows. Section I is the introduction that outlines the background to the research area of this article. Section II presents the scoping review adopted with specific examples of how this method was applied in this article. The findings from this review are outlined and illustrated with visual graphs in Section III. In Section IV, the discussion of this review is delineated, the gaps are identified and analyzed. The conclusions are drawn in Section V, where implications for practice and research along with future work are designated.

II. Methods

Scoping reviews are widely utilized by researchers who try to identify research gaps in the relevant research literature. Peters *et al.* [51] advocated that a scoping review can inform adequately others about the research questions (RQs), which could be suitable for conducting future systematic reviews and identifying implications for decision making. According to Arksey and O'Malley [52], the purpose of conducting a scoping review is to provide descriptive RQs, to analyze a comprehensive description of searching relevant articles, and to synthesize previous studies that use different types of research designs.

TABLE I
KEY SEARCH TERMS

Search Terms
("Immersive Technologies" *OR* "Virtual Reality")
AND ("Science" *OR* "Technology" *OR* "Engineering" *OR* "Mathematics")
AND ("Primary Education" *OR* "Secondary Education" *OR* "Higher Education")

Based on the above, this scoping review follows a five-stage framework underpinned by Arksey and O'Malley [52]. It is one of the most appropriate because it adopts a rigorous process of transparency. It also allows any replication of the search strategy and increases the inter-reliability of previous studies' findings. The stages are described as follows:

1) identifying the initial RQs;
2) identifying relevant studies;
3) study selection;
4) data charting and collating;
5) summarizing and reporting the results from the previous studies.

A. Identifying the Initial RQs

The current review seeks to investigate the key aspects of VR application uses and effectiveness in STEM fields to identify any possible contributions to students' learning experience, outcomes/achievements, and performance. In favor of ensuring that a substantial range of previous studies will be captured, the following RQs determine the aim of this review.

RQ1: What were the substantive features of the included studies, such as publication information, instructional context, and learners' background?

RQ2: What research methodologies were followed in the included studies?

RQ3: What is the impact of VR on students' learning outcomes and achievements?

RQ4: What technological equipment and computing devices were used in VR-supported instructional design strategies?

B. Identifying Relevant Studies

A scoping review covers a wide range of keywords and searches to collect for any terms that may be broadly adopted by previous studies [50]. Therefore, key concepts and search terms were proposed to capture the literature in STEM. The authors aggregated a sum of relevant studies. Such a decision was taken as it would be useful in the modification of key search terms to be identified the most relevant databases giving remarkable information and answering to the main RQs.

The main search concepts were as follows: 1) *VR*; 2) *immersive technologies*; 3) *K-12 education*; and 4) *HE.* To widen and combine literature searches, the techniques that were utilized by the authors for searching key terms, including the use of Boolean operators, such as OR to identify any synonyms or AND to combine search terms for each of the four main concepts. Depending on each database, the search terms were modified slightly to match the search engine's possibilities. Table I outlines the key search terms.

TABLE II
INCLUSION/EXCLUSION CRITERIA (A POSTERIORI)

Criterion	Inclusion	Exclusion
Time period	2009 to 2019	Studies outside these dates
Language	English	Non-English articles
Type of article	Original research, published in an international peer-reviewed Journal	Articles that have not well-documented the use of VR in formal or informal contexts or articles published as editorials/opinion works or in conferences
Type of method	Qualitative and/or quantitative or mixed (the combination of qualitative and quantitative data)	No method described
Study focus	Articles where the overwhelming theme relates to instructional design in different STEM fields supported by VR	Articles that made have not well-documented the use of VR in formal or informal contexts
Population and sample	K-12 or HE students	P-12 and Pre-service settings
Study concept	Articles where the overwhelming theme relates to instructional design in different STEM fields supported by immersive VR devices	Articles that made have not well-documented the use of VR and articles which focused on non-immersive VR devices such as virtual worlds or smartphone applications which can generate high or low fidelity simulation technology

To become as comprehensive as possible to answer the four RQs, a wide range of inclusion and exclusion criteria were developed. During the first-round screening, publication titles and abstracts were reviewed independently by the three authors based on *a priori* inclusion and exclusion criteria. After screening the first 94 titles and abstracts, the three authors who are experts in the *educational technology* field discovered that the concept of VR depending on previous studies is generally varied. For this reason, *a posteriori* decision to narrow uses in STEM was discussed and endorsed by the three authors. The final *a posteriori* selection criterion is outlined briefly in Table I. Each author followed first-round screening articles marked for full-text retrieval and subject to further screening against any *a posteriori* inclusion/exclusion criterion.

All articles were subjected to first- and second-round screening. As Table II presents, articles not meeting the eligibility criteria were screened out in hierarchical order depending on the type of article, study concept, and focus, and finally, on population and sample. When all articles were aggregated, the three authors discussed with consensus any possible disagreements in the selection of studies.

The authors searched eight databases focused on educational technology, computer science, and interdisciplinary subjects to cover all aspects of the topic and identify peer-reviewed literature. These databases are as follows: 1) academic search ultimate (EBSCO); 2) ACM digital library; 3) education source (EBSCO); 4) ERIC (EBSCO); 5) IEEE Xplore digital library; 6) ProQuest; 7) PsycINFO (EBSCO); and 8) Scopus. The period for the search was limited from January 2009 until the end of 2019 when this review was completed because the educational use of VR technology with innovative devices gained significant ground after 2009.

For this review, the most relevant journals, which are methodologically and scientifically relevant, were finally chosen. The google scholar h5-index for the large category of *Engineering and Computer Science* and its separated categories related to *Computer Science* and *Educational Technology* was used as a starting point. This decision was deemed as necessary since the two subcategories are more relevant to the *Education and Educational Research* and *Human–Computer Interaction* from the *Journal Citation Report Social Science Citation Index (JCR SSCI)* and the *Journal Citation Report Science Citation Index Expanded*, respectively. On one side, most of the journals relating to the educational technology are indexed together into the JCR SSCI list with journals about the educational research in general, offering a too broad foundation since the literature search can begin.

C. Study Selection

Using the key search descriptors, 94 articles were identified. A review of the abstracts revealed various articles that were irrelevant, particularly those related to HE settings. These articles were primarily associated with teaching strategies focused on the description of technical resources of using VR technology. Thus, limited evidence appeared about student evaluations and feedback, therefore, was excluded. Many articles were removed from the search as they were duplicated in six of the eight databases. Also, ten articles were identified by using a google scholar; however, only five met this review's inclusion criteria. A number of 41 ($n = 41$) studies were finally identified as relevant to the research topics of STEM. All the included articles need to be read in the full text with each one to be reviewed and confirmed as appropriate by all authors. This process was deemed as necessary, allowing being identified any relevant study by reviewing the reference list of each article. The process of article selection followed the preferred reporting of items for systematic reviews and meta-analyses statement [54], as Fig. 1 depicts.

For qualitative analysis, all the selected articles that were finally chosen had a purposeful sampling (case studies or empirical studies). To strengthen further the validity of this review, the inter-rater reliability for the quality coding of the selected articles was assessed. A subsample of 28 from a total of 39 articles (72%) was included and coded independently by the authors. The inter-rater reliability for the total scores was 0.87, showing good agreement regarding the quality of the reviewed articles that were finally included.

D. Data Charting and Collation

According to Arksey's and O'Malley's [52] fourth stage, the charting of selected articles is required. Summaries were developed depending on each article's topic, instructional study design, research methods, and sample size alongside a brief comment on the limitations and recommendations.

E. Summarizing and Reporting Findings

The last stage based on Arksey's and O'Malley's [52] review framework summarizes and reports major findings

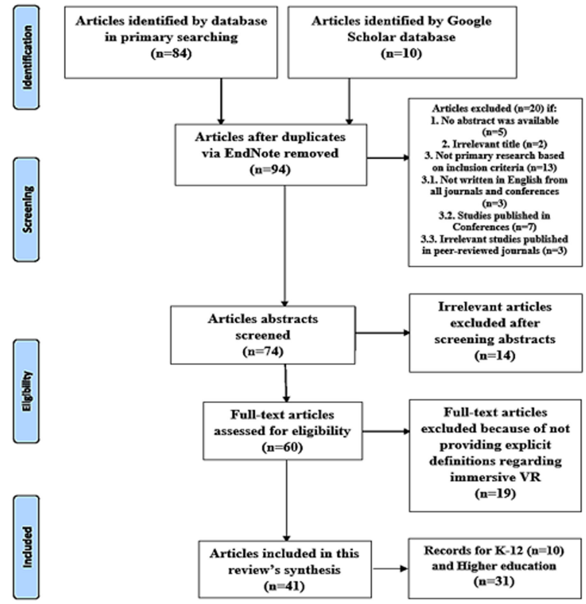

Fig. 1. Flowchart about the article selection process.

from previous studies. To delimitate instructional contexts, in which a wide range of applications and simulations were provided, it is imperative to understand the conditions under which such contexts took place. Instructional design is defined as a process that teaching and learning take place in the formal (in the class) or informal (outside the class) contexts. Within such well-designed settings, students try to carry out specific tasks in a stimulating learning environment and follow (or not) guidance provided by the instructor(s). Any predesigned approaches in which the students are engaged to achieve specific learning goals of instruction are called instructional strategies. Following the specific steps provided by Akdeniz [54], this review categorized the instructional strategies in specific groups for all the studies reviewed as follows: instruction through the presentation; instruction through the discovery; and instruction through the collaboration. A range of taxonomies designates the way that the students can gain knowledge and retrieve information to understand or interpret phenomena in-depth following instructional models, which are indicated as the sources of instructional strategies [54].

III. Results

A variety of positive contributions and challenges using VR in K-12 and HE settings are provided from the extracted data. To facilitate the discussion on the benefits and shortcomings, the authors reported a state-of-the-art overview from the analysis of all included studies to answer the four RQs.

Regarding RQ1, from the overall ten studies conducted in K-12, only one was published in 2018, and the other nine published in 2019. Six studies [9], [12]–[14], [18], [21] applied VR-supported teaching interventions in-class and four articles [6], [15], [16], [31] did not describe their learning tasks applied to the laboratories. There were none of these interventions to be applied outside of school contexts, such as in a science museum or a nature center. This shows that the technological equipment standards cannot be easily used by students due to the high cost of some computing devices and the novelty effect of using such "immersive" technologies in specific learning subjects.

From the overall ten studies, five conducted in primary education [6], [13], [14], [16], [19], four in secondary education [9], [15], [18], [21], and in only one, participants were from both primary and secondary education [12]. In most studies, the number of participants ranged from 30 to 75 (nine studies), and only one had 162 participants [15]. Also, the subject under examination was related to all fields of STEM education, which specifically are as follows: Science [6], [12], [13], Technology [9], [14], [23], [42], Engineering [19], and Mathematics [16], [18].

Regarding the duration of the interventions, half of the studies conducted in K-12 education were done in a unique session ranging from 5 to 40 min [6], [15], [16], [18], [21]. The other five [9], [12]–[14], [32] did not provide any further details.

Two studies [13], [19] followed the instruction through a presentation to enhance any provided information into a 3-D realistic simulated environment with high representational fidelity. Using VR applications, students had the chance to observe freely and choose how to explore both the content and visual elements to support simulation training. They have also engaged actively in several tasks so as to select the appropriate points of view using 3-D virtual models/animations/elements for knowledge acquisition through active instructional approaches that allowed the participants not only to observe but also to explore interactive elements, which may have an impact on students' outcomes and performance.

Five studies [6], [14], [15], [21] followed the instruction through discovery. Of these, in four studies, students tried to utilize and interact with visual elements to "learn by doing" tasks guided by the following steps: hypothesis formation, data analysis, and reflection to manipulate the learning material. Jost *et al.* [16] mentioned that the game-based learning (GBL) approaches can become more appropriate in several concepts that require *learning by doing* tasks when students can discover basic learning materials within 3-D interactive animations. If students can elaborate their material keeping in touch with 3-D visual interactive models using HMD devices, then they can answer easily with more detail. Additionally, two studies provided their findings regarding a scientific discovery instructional strategy underpinned by Piaget's theory of constructivism. This theoretical framework provides a more student-centered learning approach that requires the same students to construct knowledge on their own by exploring and discovering a 3-D environment for science phenomena [6]. Following Piaget's guidelines, Segura *et al.* [14] gave the students several opportunities to infer knowledge by interacting with 3-D digital content, such as simulation and puzzles to provide immediate feedback on users' actions through instructive-guided conditions.

Three studies ($n = 3$) were guided by instruction through collaboration. Southgate [9] reported that HMD devices assisted students to collaborate with their peers to understand the potential of *Minecraft VR* when they tried to build large-scale models in more detail. Wang [12] followed a design-based approach in which the experts and user testers worked together to design and improve a VR game called *Cellverse*. Such a process was applied in a cross-platform multiplayer VR tablet game designed for the high school students to learn fundamental biology concepts. Also, Shi *et al.* [18] assessed students' design decisions to explore, identify, and test in a daily-design activity to emerge gaming contexts into a VR simulation platform through iterative user testing for math learning (quadratic function). In all studies, VR game prototypes provided the information and/or appropriate data for the measurement of students' learning performance. Also, their findings showed an improvement in students' solutions regarding in-game problem-solving tasks.

Several studies provided evidence about the factors affecting the selection of the most appropriate instructional strategies. A major perspective is when VR-supported instruction deals with low- and high-achieving students of a different gender. In this perspective, research findings addressing the impact of VR on student learning outcomes remain mixed. For instance, Hite *et al.* [6] found that the students with lower aspects' (e.g., distance, perspective, rotation) scores contributed to knowledge transfer; however, they reported more distraction within a 3-D VR environment, thus providing lower levels of learning effectiveness. Makransky *et al.* [21] pointed out that pedagogical agents can play an important role in VR-supported learning environments depending on the participants' gender. Moreover, boys and girls are expected to provide better outcomes when interacting with the agents that have the same gender of each participant. On the role of GBL, Jost *et al.* [16] admitted that although a statistically significant effect of VR-supported interaction on mental arithmetic tasks existed, there was no significant difference found in the enjoyment of training scores between the VR and tablet training experience. Additionally, Ucar *et al.* [13] advocated that haptic feedback allows gifted students to provide better learning achievements. Another factor influencing students' learning outcomes could be in-game challenges generated by the VR devices in alignment with participation in several tasks daily [18]. The use of VR devices to support instruction through discovery indicated an effective strategy to improve students' learning achievements and outcomes in simulation-based tasks. In this perspective, several scholars and researchers [6], [15] discussed some difficulties that students might encounter in a discovery learning process and suggested that instructive-guided scaffolding tasks can overcome any frustrating tasks and drawbacks during lessons.

The research interest in recent years came with a rise focusing on the use of VR in HE settings. While only particular studies could be found in early 2009, the public availability of HMD boosted the research at the end of the decade. Most of the studies were published within the last couple of years, while the rest anywhere between 2009 and 2016, as shown in Fig. 2.

In most cases, the subject under examination was related to the science discipline ($n = 21$), whereas fewer were the attempts to explore the impact of immersive-VR tools on

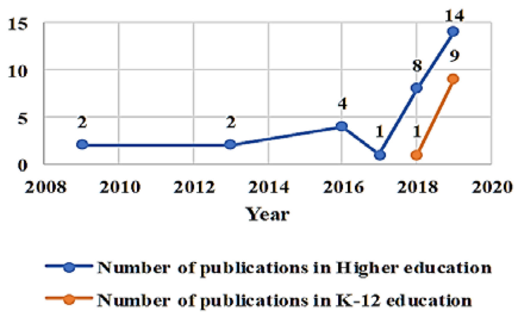

Fig. 2. Number of publications conducted in K-12 and HE settings.

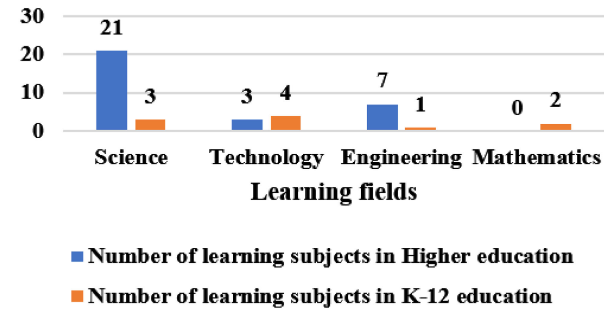

Fig. 3. Number of learning subjects in K-12 and HE settings.

matters akin to the engineering field ($n = 7$). Likewise, only a couple of attempts were identified by blending the structural elements of different disciplines, such as science and engineering. Aligned with the aforementioned educational disciplines, the participants' background included learners from different science fields, such as biology, physics, and chemistry (e.g., [22], [31], [32]), a wide range of engineers, such as electrical, mechanical, product design (e.g., [8], [47], [48]), as well as entry-level college students who undertook a simulated experience of their future "professional persona" in STEM fields [40] or outside the HE context with army soldiers undertaking simulated training tasks [34]. Fig. 3 depicts the disciplines in K-12 and HE settings.

The number of participants in studies conducted in HE varied between 13 and 200. For example, Gavish [44] researched 40 trained technicians using a self-paced training scenario for industrial maintenance and assembly tasks in VR. Greenwald *et al.* [27] compared 20 students who were familiar with the topic of magnetism using HTC Vive or a desktop monitor. Kartiko *et al.* [20] assessed the knowledge gains of 200 students without prior knowledge about a topic entitled "navigational behavior of ants." In Darabkh *et al.*'s study [37], 100 engineering students used a google cardboard with smartphones to try out drawing in engineering using VR.

As far as the demographics are concerned, all studies administered mixed-gender subjects with the minimum representative duration to be 8 min [20] and the maximum was 90 min [22]. For example, in the study of Shen *et al.* [47], the VR experience lasted only for one session, although on one occasion. The same authors reported that their participants can be fully engaged with the virtual tool for more than once. Finally, the duration of the interventions has been mainly aligned to the needs of the experiments; thus, a great gap between the minimum (5 min) and maximum (1 h and 30 min) timespans is identified. The average time that most interventions lasted is in the range from 15 to 30 min, e.g., [41] and [43]. Some investigations included studies lasting up to four weeks with repeated exercises [24], [34].

The fact that most of the studies ($n = 15$) involved the use of high-end immersive-VR equipment, be it in isolation, e.g., [30]–[32] or comparison to other tools, e.g., [29], [33], [46], restricted users' mobility and led researchers to perform their experiments in controlled environments, such as university classrooms or computer science laboratories. An exception to the rule is the case of a joint project (industry/university), where the experiment was carried out in the mixed-reality room located at the facilities of a product design company [8]. Focused subjects included a broad range of STEM topics examined soft skills cultivation, such as group work or higher order, such as problem solving, abstract thinking, altogether with self-directed learning assisted students to understand better learning materials provided by using VR applications in STEM fields [24], [29], [45].

The multidimensional nature of STEM fields that were under investigation led researchers and instructional designers to utilize different instructional approaches to cover the needs of their projects. In greater detail, the vast majority of the examined studies (17 out of the 31) opted in for the "hands on" experience using instruction through discovery, whereas 10 out of 31 studies introduced learners to the VR experience using a "passive learning" approach (instruction through presentation). Finally, four studies utilized explicitly the collaborative instructional strategy to improve the experimental learning process with group work tasks. Nevertheless, it is worth mentioning that the lack of opportunities for collaboration was mentioned as a major shortcoming, e.g., [48].

Ten studies ($n = 10$) guided by instruction through presentation approach were assessed and compared the effects of different teaching conditions or different hardware/software characteristics supported by VR. For instance, Alhalabi [41] reported that a problem-solving process using presentations without further interaction can benefit due to a higher level of user immersion. Kim *et al.* [28] found that VR technology compared with the traditional PowerPoint presentations can foster learning processes. Kartiko *et al.* [20] showed that different presentations of animated-virtual actors influence the perceived affective quality of an educational virtual environment and its learning outcomes. Bailenson *et al.* [25] investigated the effect of augmented social perception and eye gaze with VR to enhance attention. The same authors reported that the students who were in the center of the classroom during the VR presentation had additional learning benefits. Generally, the studies that promoted knowledge acquisition via presentation, such as the exploration of geographical areas, the observation of ecosystems, the simulation of career prospects required less or no active involvement from the students' side, e.g., [30], [31], [39], and [40].

Instruction through discovery was used as the instructional strategy by 17 studies. For instance, Al-Azawei *et al.* [36] carried out a study to assess whether a VR game can increase students' engagement in evaluation sessions. Chen *et al.* [42] reported that the active training of machine tools operation in training sessions embedded within a context-based teaching design exhibited superior results regarding students' learning performance compared with the sequence-based teaching design. De Klerka *et al.* [43] investigated the active building of early stage architectural models regarding the topic of organic chemistry instruction. In Edwards's and colleague's study [26], students developed and applied actively handheld molecules that lead them to higher levels of engagement, motivation, interest, and learning outcomes. Gavish [44] assessed the effectiveness of industrial maintenance and assembly tasks training through active training in AR- and VR-supported contexts. Greenwald *et al.* [27] compared students' performance in task solving in VR to 2-D settings. Jimeno-Morenilla *et al.* [45] developed a methodological approach to foster industrial design engineering and creativity skills considering activities that students were performed by using simulations, virtual reconstructions, exploration. Precisely, studies related to the sciences field (e.g., biology and chemistry) adopted a more "active learning" approach using a large variety of techniques (e.g., audio, text, illustrations, animated objects, and pedagogical agents) to introduce the subject under investigation to learners, so as to allow them to interact with the learning material (e.g., deconstruction of the main elements of a biology cell and investigation of chemical phenomena). Within such contexts, students gathered the information that could help them complete the prospect tasks (e.g., the examination of a crime scene) that allowed them to perform several simulated activities with greater confidence and accuracy [21]–[23], [31], [46]. Likewise, studies related to the engineering disciplines (e.g., electronics, mechanical, physics, and design) aimed at offering students a more "direct" experience with a touch of collaborative work [8], [47]. The main incentive behind this decision is linked to the development of a deeper understanding that abstract science phenomena require or to the delivery of a more "tangible" experience when it comes to concepts related to the geometric model development and testing (e.g., product design) [45], [47], [48].

Regarding instruction through collaboration, four studies ($n = 4$) were identified to research this instructional strategy. Abdullah *et al.* [24] investigated how problem-based learning scenarios in VR environments can enhance group work skills and self-directed learning among students. Alfalah [35] assessed teachers' familiarity with immersive technology for teaching with the result that VR can strengthen collaborative learning, engage students in learning, promote discovery learning, and achieve greater self-confidence. Darabkh *et al.* [37] developed VR games to foster cooperative drawing skills of students in engineering courses. Finally, Shen *et al.* [47] advocated that VR-supported marine engineering courses have the potential to assist students' understanding due to an increased sense of presence.

Regarding RQ2, a range of different research purposes emerged from the studies reviewed. Evaluating the effects of VR measuring students' learning gains with pre-and-post-tests was the focus of six studies in K-12 education. The user experience perspectives in VR-supported instructional contexts were investigated in four studies using different questionnaires in terms of evaluating the impact of VR applications on students' sociocognitive characteristics and assessing the impact of designing "immersive" applications for different learning purposes. All studies had only one research purpose to investigate and none of them had more than one to measure the impact of VR in teaching and learning.

Among the ten analyzed articles ($n = 10$) in K-12 education, eight were quantitative studies, two qualitative studies, and none used mixed method. All the quantitative studies employed the experimental design studies without having any quasi-experimental approach. The qualitative studies included three content analyses that were interpreted by recording material to understand knowledge construction by learners before and after a VR-supported teaching intervention by playing different game prototypes in technology [9] and science courses [12]. Both studies [9], [12] presented several key issues raised by utilizing VR applications in instructional design contexts supporting collaboration among students.

In measuring user experience in collaborative role-playing GBL contexts, researchers gained insights on the benefits of personalized learning in such environments and identified benefits on students' attention span [12]. The interpretative study of Nuanmeesri and Poomhiran [19] investigated the learning interfaces to assess the effectiveness of VR simulations in engineering courses, whereas Segura *et al.* [14] in a user experience study, traced, and documented how the instruction through discovery influenced by VR in programming. Wang [12] assessed the student's first-person embodied experience and any alternative ways that students used to understand symbols into collaborative GBL contexts.

More than 80% of the quantitative studies in K-12 reviewed (85%) described the positive impact of VR in different teaching and learning conditions. All comparative studies, which had an experimental part related to the VR-supported instructional conditions, showed that the students had greater knowledge gains compared with those who participated in non-VR ones. A remarkable point of view that was described in all studies was that VR-supported instructional design practices allowed the visualization of typically unexplored or unidentified mechanisms with high representational fidelity to display complex (or not) scientific phenomena in which students from the experimental group were immersed so that they can explore or manipulate learning materials in several tasks.

Various research purposes emerged from the studies reviewed regarding the research methods in the studies conducted in HE settings. A total of 28 studies assessed quantitative data, one was conducted using only qualitative analysis [43], and another two utilized a mixed-method approach [30], [42]. The main research objectives of the reviewed studies can be classified into three broad themes as follows:

1) the examination of the educational potential of immersive technologies (66%);
2) the impact of immersive-VR tools on learners' behavior (40%);
3) challenges or opportunities of the educational VR-supported solutions from the user experience perspective (20%).

The scholars utilized a variety of research methods (e.g., surveys, open-ended questions, reports, recordings, observations, knowledge, and behavior tests) with the most dominant ones being the mixed methods strategy. Precisely, 73% of the studies included at least one survey, which aimed at examining participants' emotional statement about VR usage (e.g., presence, satisfaction, motivation, and simulator sickness), e.g., [22], [23], and [32]. Such studies were focused more on the educational potential of the VR tools that included several knowledge-based tests, which examined either the immediate learning gains [30], [47] or long-term ones (e.g., knowledge transfer/retention) [38]. Moreover, studies investigated the impact of the intervention (e.g., knowledge acquisition, learning outcomes, and achievements) and the effects of VR tools on students' behavioral experience originated from the custom-made tools (e.g., pre-/post-tests or the participants' observations), e.g., [8], [39], and [47], when analyzing the data collection protocol that was applied in articles to identify factors affecting the user experience. Precisely, researchers who explored in this direction employed (primarily) a set of well-known evaluation mechanisms, such as the system usability survey, the simulator sickness questionnaire, and the game engagement/experience questionnaire. Also, the use of some tailor-made instruments aimed at investigating the benefits and challenges of using VR tools either on students' performance and outcomes or user experience [32], [39], [48].

For the quantitative studies, most investigations conducted pre- and post-tests to measure learning gain or only post-tests to measure students' learning achievements/outcomes or performance. Some others examined user experience using questionnaires with high construct validity [37] or recall questionnaires [25]. For instance, Kartiko *et al.* [20] assessed emotional states next to performance tests and tests for presence. In doing so, research on how VR in HE settings can benefit by collecting data from quantitative approaches to understand better the effects of immersive media on learning outcomes while thriving on additional measures, such as emotional states, presence, and perceived usability. Many samples had small sampling to gather definite conclusions on the true impact of immersive media on learning either in formal or informal settings to answer if VR applications can contribute to the discussion on their use in the future.

Concerning RQ3, four studies ($n = 4$) in K-12 examined the impact of applications generated by VR devices on user experience. The remaining six ($n = 6$) provided evidence on the impact of various applications. Based on the assessment methods followed by ten studies reviewed, a clear classification into two broad categories provided evidence regarding students' outcomes and performance: user experience and comparative studies. The first category includes several aspects of the use of VR as stated in the investigation of students' attendance, deep knowledge, and understanding of several K-12 subjects. For instance, Nuanmeesri and Poomhiran [19] found that elementary students were able to apply the knowledge gained in constructing and fixing electrical circuitry. Segura *et al.* [14] showed that the students were more engaged inside a 3-D virtual environment called *VR-OCKS* rather than when they participated in any other learning task. The same researchers have pointed out that many students were also focused on the tasks to learn how to program to utilize properly fundamental programming constructs in problem-solving conditions. In science courses, students participated in role-playing collaborative settings. They also seemed to be less engaged in-class, which conceptualize their plants, but more engaged in building plants using VR [9]. Finally, Wang [12] advocated that the user experience feedback regarding the game difficulty allowed students to shape a gameplay experience that would be provided as a challenge without making the solution too easy or infuriating in order to be properly solved.

The second major category entails studies focused on the measurement of students' understanding of several learning concepts associated with cognitive outcomes, achievements, and performance. In most studies conducted in K-12 subjects, the researchers used pre-/post-test formats with multiple-choice or short-answer questions to assess the retention of the presented material. A significant number of comparative studies were conducted. Chen [15] mentioned that while the participants who learned several key topics related to STEM and technology using VR performed greater to a cyclical learning pattern, their counterparts who learned via lectures produced a linear one without having the appropriate visual feedback. Using pre- and post-tests, Hite *et al.* [6] evaluated several tasks related to the spatial acuity of secondary education students and indicated that VR applications can play an important role in science courses. Within GBL contexts, a 3-D VR environment can add to the mental arithmetic task enjoyable and motivating experience on students' outcomes [16]. Also, Shi *et al.* [18] developed and applied a game prototype using VR technology. The results from their study showed that students in math tests about quadratic function had significant improvements in post tests than in pre tests, as provided by the grades from the experimental group compared with their counterparts in the control. In the same study, a learning motivation survey demonstrated a significant improvement in students' motivation for knowledge acquisition in mathematics. Makransky *et al.* [21] urged on the use of VR applications where middle school girls and boys learned better with different kinds of on-screen agents across three different measures of learning in problem-solving tasks. Pre-and post-test scores in knowledge transfer and learning performance measurements during the simulation were higher for boys than girls. Finally, Ucar *et al.* [13] noticed that the gifted students from the experimental group who used VR in computer science courses had more positive thoughts about haptic applications, as they were more productive compared with nonimmersive-VR-supported approaches that a control group was followed.

Despite the general positive aspects on the use of VR technology in K-12 STEM fields, only five studies reported problems and challenges influencing the effectiveness of learning tasks. These are as follows.

1) Technological equipment limitations may sometimes create a 3-D UI that will not be intuitive to be created effective conditions for educational purposes [12].

2) A limited number of only six or seven students within collaborative instructional settings could be easily controlled by the instructor due to the equipment's quantitative restrictions [15].
3) Students' aspects (positive or negative) influencing the degree of knowledge diffusion depending on the control of gender ratio in an unequal gender school [21].
4) GBL approaches in mathematics were utilized mostly for abstract knowledge and not for more complex concepts [18].
5) On-going problem-solving tasks required realistic instructional design in-class conditions to acknowledge the effectiveness of VR-supported instruction [9].

Previous efforts that assessed different VR-supported instructions in HE settings offer contradictory results. For instance, as Makransky *et al.* [22] reported, the cohort that undertook biology simulations in a desktop-VR setting achieved better learning outcomes when compared with the cohorts that experienced the same simulation in a VR environment. In Selzer *et al.*'s [39] study, engineering students demonstrated better learning performance and accomplished greater learning achievements when used a high-end or even a low-end immersive-VR solution as opposed to the cohort that performed similar tasks in a desktop-based VR environment.

However, when comparing the educational potential of high-end VR solutions (i.e., room-scale VR) to that of the low-end ones (i.e., mobile VR), a mutual agreement is identified. As previous studies [23], [39] suggested, the added value of immersive VR is linked (directly or indirectly) to the sense of presence. The notion under this claim is further elaborated to the degrees of immediate control and autonomy that users develop due to the high representational fidelity of visual elements using VR. It can, therefore, be concluded that the levels of presence that learners reached by a given technological device affected various cognitive (e.g., attention, memory, and reasoning) and noncognitive (e.g., satisfaction, perceived learning, and intention to use the simulation) factors. Such factors are of great importance to define the success of the teaching intervention, and thus the learning outcomes.

A significant number of studies reported some positive benefits retrieved by using VR. These are as follows.

1) It enhances group work skills and self-regulated learning among students [24].
2) It increases students' engagement in collaborative learning tasks, such as discovery and problem solving [35].
3) It improves learners' outcomes using an immersive work interface allowing immediate 3-D conceptual design and presentation experience [48].
4) It assists groups to achieve better design-related flaws using VR than using other design "tools," such as Creo view [8].
5) It increases students' attention to "learn by doing" experimental tasks [25].
6) It supports more effective than learning through the traditional lecture-based methods in which PowerPoint was utilized [28].

Three studies ($n = 3$) reported an increased level of students' engagement alongside the positive effects of VR that lead to better learning outcomes and achievements. In particular, better attention, learning outcomes/achievements, and behavioral changes of students were reported as some of the effects of using VR [25]. For instance, Chen [15] postulated that combining a teaching method with VR technology can enhance learning activities, when assessing comparisons between VR and AR groups supporting industrial maintenance and assembly tasks training. Edwards *et al.* [26] argued that VR triggered students' attention, interest, and motivation in science courses.

However, six studies reported no statistically significant differences by using VR. Results from previous studies indicated that there are no differences in presence, perceived effective quality, or learning outcomes [20], and no significant difference between 2-D and VR-supported instructional design practices, when comparing the percentage of improvement over the baseline for each session [27]. Additionally, no difference related to the symptoms of discomfort between the cohorts who received pretraining and those who had not. Also, the immersive-VR simulation cohort had significantly the higher negative symptoms of discomfort, while immersive/nonimmersive VR improved the students' understanding of relative motion concepts [38]. In another study, there was no significant difference in the epistemological belief questionnaire between the students with/without prior background in physics. Nonetheless, all students' learning performance has significantly improved [29]. Also, no difference between the cohorts' prior experience in VR and physical STEM courses was found [40]. Studying the integration of two different "immersive" technologies in engineering courses, there were fewer unsolved errors in the AR group (treatment) compared with the control-AR groupand no significant differences in the final performance between the VR and the control-VR groups [44].

A portion of scholars compared a set of conventional media with different VR settings and educational setups. Starting from the most traditional approach (i.e., textbooks), the results indicate a clear superiority of the VR-supported solutions on intrinsic motivation and knowledge transfer without. However, no significant difference in the effectiveness of the medium to aid the development of knowledge was found [46]. The transition from the "traditional" digital learning tools (e.g., 2-D desktop-based animations) to the more advanced 3-D immersive environments can be equally effective. As suggested by Limniou *et al.* [31], the use of VR for teaching chemistry enabled the students to develop stronger conceptual understanding and make a better sense of the procedural implications that such topics inherently present.

On the antipode, those who examined the efficiency of different solutions using VR technology against the other 3-D tools (e.g., dedicated software for geometric modeling) reported better outcomes in the favor of the later [47]. This is also in agreement with the findings reported by Webster [34] who further noticed that especially in large group settings, preference should be given to the traditional tools and instructions. Nonetheless, an approach to improve the efficiency and effectiveness of VR-supported teaching interventions is suggested by Meyer *et al.* [38] who used different instructional methods (e.g., pictures, videos, and VR) as a part of the pretraining process. This is hard to propose an all-rounder combination, which can serve all the educational purposes and cover all the very different needs. However, it can be concluded that pretraining should be an essential part of any intervention, which involves the use of VR tools.

To sum up, VR in STEM offers various opportunities for enhancing factors that are relevant for learning. While it cannot be assumed that the technology itself is responsible for the learning outcomes, other variables, such as presence and emotional states, can be induced using VR contributing to learning activities. Furthermore, engagement as a key factor of the constructivist's perspective on learning processes (which is particularly important for STEM subjects) can be fostered using immersive media.

Concerning RQ4, nine studies ($n = 9$) created a wide range of VR applications in K-12 education. Only one study utilized *Minecraft VR* [9]. The current review categorizes educational VR applications in K-12 as follows:

1) exploration with high representational fidelity, with the use of a point of interest to trigger digital information (four applications);
2) simulation tools (four applications);
3) game prototypes (two applications).

Regarding the type of digital element for developing visual features used by VR applications, 65% of the studies reviewed 3-D models, nearly less than half of them (42.8%) used as well as 2-D images. Almost nearly a third percentage (32.1%) used several animations in GBL settings, e.g., [16]. Some applications provided audio information (10.7%) and others connected with design-based tasks in a 3-D environment, such as *Minecraft VR* using Oculus Rift (7.1%) [9].

HMD devices can support embodied interaction, which is recognized by a large body of literature as the most extensively used category of "tools" in K-12 education. An indicative explanation could be that courses specifically in STEM education applied in-class and/or in laboratories demand mobility and free exploration of visual elements, which are important aspects for knowledge acquisition. Another aspect is the fact that VR applications generated by mobile devices are more frequently utilized for collaborative tasks within real-world instructional contexts since technological equipment is already installed in school laboratories. A variety of previous studies created VR applications using HMD devices, such as Oculus Rift [9], [12], HTC Vive [14], [18] and Samsung GEAR VR [16], [21], while fewer developed their VR applications using zSpace AIO computer system using share screen, stylus screen, webcam, and stereo glasses [6], [15].

Regarding the building tools used in ten K-12 studies reviewed, most of these were self-developed and self-programmed native VR applications. Two studies provided more information on the development of VR applications and UI design, and 3-D modeling built in unity and programmed in Visual C++ [13], or Blender and Maya [12].

In regard to the investigations focusing on HE settings, VR-supported instructional design practices varied as several computing systems exploited, such as CAVE [31], [41], desktop-based screens [15], [24], cardboards [37], [45], Oculus Rift [39], Samsung Gear VR [32], [36], [38], other smartphones to support VR settings [26], [43], and HMDs [27], [30], [38], [41]. Therefore, the use of HMDs either with mobile VR or standalone devices dominates the research field.

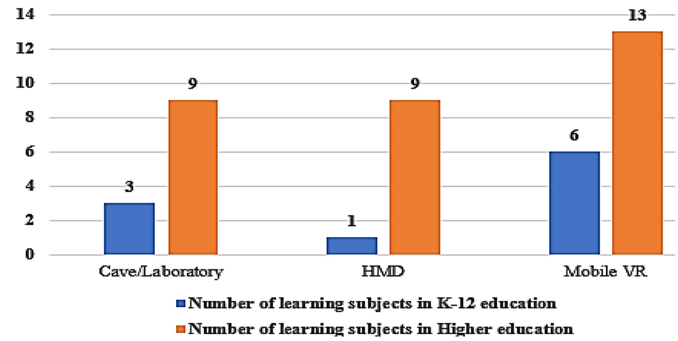

Fig. 4. Technological equipment in K-12 and HE settings.

As some of the studies measured usability, VR is presented as a superior medium that can be widely used in comparison with the traditional lecture-based methods with PowerPoint [28]. Other studies could show that VR drawing systems for architecture and engineering can be easier to use than the desktop-based versions of the respective software due to their 3-D characteristics, which are more acceptable by users [37], [43]. The technological features of educational VR included mostly current HMDs in the form of mobile VR headsets or standalone systems with handheld controllers (e.g., [30] and [48]). As usability in VR environments is important for user experience, corresponding measures are the important indicators of successful learning experiences as well [8], [23].

As the technological evolution of VR technology advances, the price of the VR devices decreases. This is also confirmed in the context of this review, as 60% of the included studies utilized high-end immersive setups, such as CAVE, HTC Vive, and Oculus Rift, while nearly 30% of them to utilize low-end solutions, such as VR boxes or mobile phones with HMD and handheld controllers. There is an obvious shift using large-screen systems/laboratory settings, such as the CAVE toward more portable mobile VR devices and other, and more professional forms of HMDs within the recent years (see Fig. 4).

Besides that, in cases where the high levels of fidelity and attention to detail were required, the additional tools are being mentioned (e.g., [29] and [34]). In either case, a portion of scholars (26%) decided to outsource the development process, thus reporting the names of the companies that undertook this task, e.g., [22], [30], and [46]. For instance, any commercially available solution to develop virtual content, such as the Autodesk 3ds Max and the Unity 3-D, was preferred by many researchers for the creation of textures and the orchestration of the interactive elements of the interventions, respectively.

Almost all the reviewed papers in HE settings utilized at least one high-end or low-end VR tools, be it in an isolation (e.g., [30], [31], and [40]) or as a comparison measurement [22], [29], [46]. In nearly half of those cases, the findings from the immersive-VR tools were compared with the educational achievements that students reached while undertaking a similar or identical experience in the standardized desktop-based VR setup. Nevertheless, as the main objective of those studies was to compare and assess the educational impact of immersive VR and not the technical characteristics of the tools, in most cases the provided information was restricted to a brief mention of the hardware components and the relevant fine details. Thus, the solutions described later in the text do not reflect the whole number of the considered studies but most of them.

IV. Discussion

Learning tasks using immersive technologies have steadily gained popularity over the past decade due to the advancement of VR and the growing need for simulations and learning environments in STEM fields. VR provides various learning benefits as students can have access to high-quality educational resources with realistic simulated representational fidelity generated by computing devices. Simple technical solutions, such as mobile VR, can be considered as a low cost while still providing experiences that are independent in their spatial-temporal constraints and time limits. With the continued expansion of VR using HMD and mobile devices, a multitude of simulation-based learning platforms provides a wide number of instructional modules.

The current review highlights the use of different VR applications in STEM learning subjects that have not yet been investigated. Based on the findings from previous studies, the instructors, researchers, and scholars who found VR integration within their courses more challenging are those who have extensive experience in the use of mobile and high-end computing devices. A substantial body of previous studies [6], [13], [14], [18] has come to the conclusion that the integration of learning content using 3-D UI design concepts and motion sensing devices allows body gestures for hands on experience, with the goal to transform the educational processes of formal teaching and learning toward enjoyable and engaging learning activities. To this notion, students assisted in "learning by doing" tasks and explore learning materials within predefined instructional design contexts.

A remarkable number of different research methods were provided over a short period for assessment usually on the same day of the intervention. Hence, future works need to investigate whether students in K-12 education preserved the same positive results on a long-term basis, e.g., several months or even years after a VR-supported teaching intervention. Furthermore, some of the reviewed studies were focused on the quantity of learning gain through pre- and post-tests within specific time frames without analyzing any positive and negative emotional statements of users using other mechanisms that can provide visual analytics during the experimentation process. Even if VR equipment has not a minimum age range restriction, an investigation to understand any physical effects, such as sickness, fatigue, and dizziness, for students in K-12 education is still on its infancy.

Several benefits of VR-supported instruction were broadly well documented by the relevant literature (e.g., increased motivation when compared with ordinary exercises, higher levels of satisfaction, better learning performance, and achievements in the short- or long-term tests as well as in other but similar conditions), mostly in HE settings. Thus, VR possesses a strong foundation since further research and development should be performed to improve and enhance the educational potentials in STEM. The most remarkable points of view from the studies that were conducted in HE settings revealed that there is still no tool or approach capable of covering all the different learning scenarios and needs without a flaw. On a further breakdown, the examined cases highlighted that the key ingredients that make STEM-related educational activities successful and effective in such contexts are mainly depending on the instructional design decisions and methods.

On the one side, the choice of the toolbox (i.e., software/hardware) and the respective technical limitations can greatly affect the outcome. In addition, the lack of longitudinal studies to provide theoretical and conceptual frameworks hardens, even more, the current situation, which is also what motivated the conduct of this study. Beyond that, the high graphics resolution and the strong computing power that modern VR tools allowed researchers and instructional designers to develop real-world simulated scenarios with high fidelity and clarity [8], [23], [47]. In return, students can experiment safely without restrictions deriving from the learning material and experience the knowledge, thanks to the high degree of realism that the simulated scenarios offer. Moreover, the inherently ludic nature of VR leads students to be immersed [27], [31], [39] and enables them to develop different cognitive attributes that can lead to the displacement of intuitive misconceptions with more accurate mental models [29]. In addition, the opportunities for collaboration in all the different setups are highly appreciated as the risk of exclusion is decreased, and the success of the intervention increases [8].

On the other side, the cost of the technological equipment (mainly applicable to high-end setups) and the preparation required for the design, the development, and the optimization of such interventions make the application of such solutions less viable, especially in large-scale scenarios [32], [34]. Another aspect that must be considered the technical glitches (e.g., frame-rate desynchronization, freezes, and loading speed), which may occur or even the difficulty to use mobile VR devices. Some users may not have any previous experience and familiarity with such tools as they both break the sense of presence and degrade the value of the learning experience [22], [23], [30], [46], [47]. The use and efficiency of VR strongly depend on the available hardware and software. Even though mobile VR is a simple way to provide an immersive experience, new technologies adding positional tracking to devices such as *Oculus Quest* or *Oculus Go* can "immerse" students too. Finally, the lack of real-time collaborative and decision-making "tools" has received limited attention due to the rather individualized technical nature of such devices. Nonetheless, it has been highlighted as an aspect of major importance that is still missing from previous studies [8], [48].

This review suggests that interactive learning challenges using VR generated by HMDs should be designed carefully for various learning tasks through instructive-guided approaches beyond "typical" in-class contexts, such as field trips and museums to support further in/-formal teaching contexts. For example, students' learning experience improvements succeed by using well-known HMD devices, such as Samsung Gear, that might be reflected in gender equity [21] that can lead to playful learning tasks for knowledge gain, interaction with 3-D learning materials, and enhanced collaboration, e.g., [9] and [12]. Following a constructivist's point of view, the most effective VR-supported instruction was through the discovery approach. Also, instruction through collaboration seems to be an interesting research area for future research. While not many efforts guided by this instructional strategy due to its current complexity to be carried out, future advances in VR software development and hardware may pave the way for this innovative research branch [14], [19], [42], [43].

This scoping review advances the current understanding of the role of VR in teaching and learning processes in diverse spaces, structures, and interactions into the formal and informal instructional design contexts. It is also in line with previous reviews [49], [51], which provided several perspectives from the implementation of more experimental studies to investigate the effectiveness of VR applications in different STEM fields. Beyond the fact that many studies presented evidence based on various assessment research methods, this review unveils that such methods limited to the presentation of findings focused on student engagement, potential improvements on teaching and learning, measurement of learning gain, and user experience feedback [15], [16]. While such methods can give valuable information on the role of VR in STEM education, there is much more work to be done by providing evidence reflected by analyzing the overall impact on students' learning performance.

V. Conclusion

This scoping review provides a state-of-the-art overview of how VR has been widely conceptualized, operationalized, contextualized, and evaluated over the past ten years in STEM fields. The results showed the potential of using different devices that can generate VR applications to support instructional design contexts. This technology advances learning as indicated by students' positive attitudes, engagement, learning outcomes, achievements, and performance across different STEM fields. The main opportunity mentioned by previous studies was that students had the opportunity to control learning materials in "hands-on" tasks and had immediate feedback on their actions during the execution time. VR assisted students to transfer their experiences and previous knowledge within specific instructional design contexts, leading to their conceptual understanding improvement. This may also assist students' knowledge acquisition, visualization of their ideas, and reflection upon their self-learning experiences.

Although the most remarkable potentials that VR provides are well-documented, some notable key challenges need to be reported. For instance, issues such as the lack of course structure, instructional design contexts, and time require further attention. From the instructor's side is to prepare or create any learning material. From the students' side is to master it properly due to their limited experience with immersive technologies that were commonly reported by previous studies. Another significant challenge is associated with Engineering courses in K-12 education. The use of VR applications could assist students in such disciplines, possibly because immersive technologies can promote practice-based tasks in specific contexts, such as simulations in virtual laboratories. Nonetheless, understanding the challenges that students face using VR devices in STEM fields can assist instructional designers to propose effective interventions and eliminate any possible boundaries.

Notwithstanding the foregoing, this review has some noticeable limitations. First, the search selection criteria and methodology to aggregate articles to consider only those published by international peer-reviewed journals decrease the total number of articles included in this scoping review. As many presentation types and topics for conferences alongside those from published books may vary from the journals' perspectives, the results might have slightly differed. Second, this review's findings are restricted by focusing solely on studies that used immersive VR, and not, for example, on nonimmersive VWs, such as SL, which might have offered more insights into the identified challenges. Third, another notable limitation is that all the included articles were written only in English. Including results from other languages might contribute to gather and compare international research efforts. Fourth, this review is not exhaustive, since there are appeared some databases, which do not provide the possibility to access all full texts without payment, such as IGI Global. Consequently, some studies could not be found and analyzed.

VI. Implications for Practice and Future Research

The findings from this review can be used by educational practitioners and instructional designers to understand how VR can improve students' learning outcomes and achievements. The present review extends the state-of-the-art overview of the impact of VR and devices. It provides evidence from previous studies' results that used HMD devices but without mentioning clearly how instructors supported and how they provided feedback on students' actions during the learning procedures. A notable practical implication based on the findings from the current review is that VR application designers and developers should consider including the instructor's presence to guide and facilitate learning tasks that may assist students' engagement during any learning procedure. Instructors should consider the replication of practices from the instructor's side to deliver an appropriate quantity of visual "checkpoints" or immediate (non)verbal communication to assist users accomplish specific objectives and proceed to the next level.

From an instructional designer's perspective, given the similar educational potential that the high-end and the low-end VR tools have, it is suggested that inexperienced educators and practitioners use mobile VR approaches as a stepping stone before making larger and more demanding investments [15], [22]. Considering the potential shift or future transition from the "traditional" computer-/desktop-based educational tools to the next-level haptic enabled devices, a possible way forward may include the embodiment of such tools in the context of the traditional curriculum can enable learners to develop the required familiarity and confidence.

From an application developer's and designer's perspective, features such as visual appearance, navigation, and interaction with visual objects can influence positively or negatively users' presence or experience. As presence shows high educational merit as a predictor for learning activities as well [55], subjective perceptions can also be crucial for the educational value of a VR application. Thus, some recommendations that can be proposed in STEM fields and associated with different instructional strategies are as follows.

1) The use of mindful abstractions and metaphorical representations with realistic simulated fidelity, which are being projected by mobile or desktop devices, such as its architecture, realistic visualization, and configuration of objects can enhance the learning of new concepts guided by instruction through presentation [13], [19], [20].
2) The characteristics of multiple kinesthetic styles, such as moving digital content within predetermined instructional contexts, communicating through gestures or speech can assist users to understand how to use any projected perspective guided by instruction through collaboration [18], [37], [47].
3) The visual features are required to be digitally tangible to assist interact with complex or simpler automation mechanisms, such as door-opening, elevator function, teleportation, and warning messages, agents with human characteristics can provide appropriate feedback guided by instruction through discovery [21], [27], [45].

The current review adds useful information to the existing literature. Nevertheless, it is important to mention its limitations based on previous studies' findings, which could be addressed in future research. Although VR is on its rise and is widely used in STEM fields, there is a lack of longitudinal studies to inform course instructors regarding the effectiveness of this technology in different learning subjects. First, due to the limited number of comparative studies, it is difficult to recognize any learning gain of VR usage in STEM fields, since participants may not have pre-existing (theoretical) knowledge of topics and/or the technology itself. Hence, it would be not able to determine any potential improvements in students' learning performance. Second, many studies were focused on VR uses explicitly in science courses. This implies that VR was mostly utilized in laboratory courses, which may not allow us to generalize the current findings to other interdisciplinary fields, such as engineering and mathematics in K-12 education. Third, there was no evidence gathered by the data analytics from participants who took part in each study during their learning procedure as HMD devices are still today mentioned as trends.

Future works should clarify whether VR applications can be effortfully utilized across other subject matters. Furthermore, it has to be noted that there are multiple person-specific (e.g., individual perception, cognitive capabilities, subjective states, and traits) and technological (e.g., level of immersion, content factors, interaction) factors influencing immersive experience in teaching and learning. Devices including head sensors and eye trackers could give additional insights into learner behavior for future studies to gain a better understanding of thinking processes and user interaction. Future works should consider the impact of external factors, such as the instructor's presence on students' learning outcomes and performance.

References

[1] "Explore." [Online]. Available: https://nsf.gov/nsb/sei/edTool/explore.html, Accessed on: Jul. 27, 2019.
[2] N. Pellas, I. Kazanidis, and G. Palaigeorgiou, "A systematic literature review of mixed reality environments in K-12 education," *Educ. Inf. Technol.*, vol. 25, no. 4, pp. 2481–2520, 2020.
[3] V. Potkonjak *et al.*, "Virtual laboratories for education in science, technology, and engineering: A review," *Comput. Educ.*, vol. 95, pp. 309–327, 2016.
[4] R. Schroeder, *Possible Worlds: The Social Dynamic of Virtual Reality Technology*. Boulder, CO, USA: Westview, 1996.
[5] M. Slater, "Measuring presence: A response to the Witmer and singer presence questionnaire," *Presence Teleoperators Virtual Environ.*, vol. 8, no. 5, pp. 560–565, 1999.
[6] R. L. Hite *et al.*, "Investigating potential relationships between adolescents' cognitive development and perceptions of presence in 3-D, haptic-enabled, virtual reality science instruction," *J. Sci. Educ. Technol.*, vol. 28, no. 3, pp. 265–284, 2019.
[7] Z. Merchant, E. T. Goetz, L. Cifuentes, W. Keeney-Kennicutt, and T. J. Davis, "Effectiveness of virtual reality-based instruction on students learning outcomes in K-12 and higher education: A meta-analysis," *Comput. Educ.*, vol. 70, pp. 29–40, 2014.
[8] J. Wolfartsberger, "Analyzing the potential of virtual reality for engineering design review," *Autom. Construct.*, vol. 104, pp. 27–37, 2019.
[9] E. Southgate, "Embedding immersive virtual reality in classrooms: Ethical, organisational and educational lessons in bridging research and practice," *Int. J. Child-Comput. Interact.*, vol. 19, pp. 19–29, 2019.
[10] M. M. Schmidt, C. Schmidt, N. Glaser, D. Beck, M. Lim, and H. Palmer, "Evaluation of a spherical video-based virtual reality intervention designed to teach adaptive skills for adults with autism: A preliminary report," *Interact. Learn. Environ.*, pp. 1–20, 2019.
[11] S.-C. Chang, T.-C. Hsu, W.-C. Kuo, and M. S.-Y. Jong, "Effects of applying a VR-based two-tier test strategy to promote elementary students' learning performance in a geology class," *Brit. J. Educ. Technol.*, vol. 51, no. 1, pp. 148–165, 2020.
[12] A. Wang, "Iterative user and expert feedback in the design of an educational virtual reality biology game," *Interact. Learn. Environ.*, pp. 1–18, 2019.
[13] E. Ucar, H. Ustunel, T. Civelek, and I. Umut, "Effects of using a force feedback haptic augmented simulation on the attitudes of the gifted students towards studying chemical bonds in virtual reality environment," *Behav. Inf. Technol.*, vol. 36, no. 5, pp. 540–547, 2016.
[14] R. J. Segura, F. J. del Pino, C. J. Ogáyar, and A. J. Rueda, "VR-OCKS: A virtual reality game for learning the basic concepts of programming," *Comput. Appl. Eng. Educ.*, vol. 28, no. 1, pp. 31–41, 2020.
[15] J.-C. Chen, "Developing a hands-on activity using virtual reality to help students learn by doing," *J. Comput. Assisted Learn.*, vol. 36, no. 1, pp. 46–60, 2020.
[16] P. Jost, S. Cobb, and I. Hämmerle, "Reality-based interaction affecting mental workload in virtual reality mental arithmetic training," *Behav. Inf. Technol.*, pp. 1–17, 2019.
[17] F. Blume, R. Göllner, K. Moeller, T. Dresler, A. Ehlis, and C. Gawrilow, "Do students learn better when seated close to the teacher? A virtual classroom study considering individual levels of inattention and hyperactivity-impulsivity," *Learn. Instruct.*, vol. 61, pp. 138–147, 2019.
[18] A. Shi, Y. Wang, and N. Ding, "The effect of game–based immersive virtual reality learning environment on learning outcomes: Designing an intrinsic integrated educational game for pre–class learning," *Interact. Learn. Environ.*, pp. 1–14, 2019.
[19] S. Nuanmeesri and L. Poomhiran, "Perspective electrical circuit simulation with virtual reality," *Int. J. Online Biomed. Eng.*, vol. 15, no. 5, p. 28, 2019.
[20] I. Kartiko, M. Kavakli, and K. Cheng, "Learning science in a virtual reality application: The impacts of animated-virtual actors' visual complexity," *Comput. Educ.*, vol. 55, no. 2, pp. 881–891, 2010.

[21] G. Makransky, P. Wismer, and R. E. Mayer, “A gender matching effect in learning with pedagogical agents in an immersive virtual reality science simulation,” *J. Comput. Assisted Learn.*, vol. 35, no. 3, pp. 349–358, 2019.

[22] G. Makransky, T. S. Terkildsen, and R. E. Mayer, “Adding immersive virtual reality to a science lab simulation causes more presence but less learning,” *Learn. Instruct.*, vol. 60, pp. 225–236, 2019.

[23] G. Makransky and L. Lilleholt, “A structural equation modeling investigation of the emotional value of immersive virtual reality in education,” *Educ. Technol. Res. Develop.*, vol. 66, no. 5, pp. 1141–1164, 2018.

[24] J. Abdullah, W. N. Mohd-Isa, and M. A. Samsudin, “Virtual reality to improve group work skill and self-directed learning in problem-based learning narratives,” *Virtual Reality*, vol. 23, no. 4, pp. 461–471, 2019.

[25] J. N. Bailenson, N. Yee, J. Blascovich, A. C. Beall, N. Lundblad, and M. Jin, “The use of immersive virtual reality in the learning sciences: Digital transformations of teachers, students, and social context,” *J. Learn. Sci.*, vol. 17, no. 1, pp. 102–141, 2008.

[26] B. I. Edwards, K. S. Bielawski, R. Prada, and A. D. Cheok, “Haptic virtual reality and immersive learning for enhanced organic chemistry instruction,” *Virtual Reality*, vol. 23, no. 25, pp. 363–373, 2019.

[27] S. W. Greenwald, W. Corning, M. Funk, and P. Maes, “Comparing learning in virtual reality with learning on a 2D screen using electrostatics activities,” *J. Universal Comput. Sci.*, vol. 24, no. 2, pp. 220–245, 2018.

[28] S. Kim *et al.*, “Virtual reality visualization model (VRVM) of the tricarboxylic acid (TCA) cycle of carbohydrate metabolism for medical biochemistry education,” *J. Sci. Educ. Technol.*, vol. 28, no. 6, pp. 602–612, 2019.

[29] M. Kozhevnikov, J. Gurlitt, and M. Kozhevnikov, “Learning relative motion concepts in immersive and non-immersive virtual environments,” *J. Sci. Educ. Technol.*, vol. 22, no. 6, pp. 952–962, 2013.

[30] R. L. Lamb and E. A. Etopio, “Virtual reality simulations and writing: A neuroimaging study in science education,” *J. Sci. Educ. Technol.*, vol. 28, no. 5, pp. 542–552, 2019.

[31] M. Limniou, D. Roberts, and N. Papadopoulos, “Full immersive virtual environment CAVE™ in chemistry education,” *Comput. Educ.*, vol. 51, no. 2, pp. 584–593, 2008.

[32] J. Pirker, I. Lesjak, and C. Güetl, “An educational physics laboratory in mobile versus room scale virtual reality—A comparative study,” *Int. J. Online Eng.*, vol. 13, no. 8, 2017, Art. no. 106.

[33] W. Tarng, C.-Y. Lee, C.-M. Lin, and W.-H. Chen, “Applications of virtual reality in learning the photoelectric effect of liquid crystal display,” *Comput. Appl. Eng. Educ.*, vol. 26, no. 6, pp. 1956–1967, 2018.

[34] R. Webster, “Declarative knowledge acquisition in immersive virtual learning environments,” *Interact. Learn. Environ.*, vol. 24, no. 6, pp. 1319–1333, 2016.

[35] S. F. M. Alfalah, “Perceptions toward adopting virtual reality as a teaching aid in information technology,” *Educ. Inf. Technol.*, vol. 23, no. 6, pp. 2633–2653, 2018.

[36] A. Al-Azawei, W. Baiee, and M. A. Mohammed, “Learners’ experience towards e-assessment tools: A comparative study on virtual reality and Moodle quiz,” *Int. J. Emerg. Technol. Learn.*, vol. 14, no. 5, pp. 34–50, 2019.

[37] K. A. Darabkh, F. H. Alturk, and S. Z. Sweidan, “VRCDEA-TCS: 3D virtual reality cooperative drawing educational application with textual chatting system,” *Comput. Appl. Eng. Educ.*, vol. 26, no. 5, pp. 1677–1698, 2018.

[38] O. A. Meyer, M. K. Omdahl, and G. Makransky, “Investigating the effect of pre-training when learning through immersive virtual reality and video: A media and methods experiment,” *Comput. Educ.*, vol. 140, 2019, Art. no. 103603.

[39] M. N. Selzer, N. F. Gazcon, and M. L. Larrea, “Effects of virtual presence and learning outcome using low-end virtual reality systems,” *Displays*, vol. 59, pp. 9–15, 2019.

[40] C. R. Starr, B. R. Anderson, and K. A. Green, “‘I’m a computer scientist!’: Virtual reality experience influences stereotype threat and STEM motivation among undergraduate women,” *J. Sci. Educ. Technol.*, vol. 28, no. 5, pp. 493–507, 2019.

[41] W. Alhalabi, “Virtual reality systems enhance students’ achievements in engineering education,” *Behav. Inf. Technol.*, vol. 35, no. 11, pp. 919–925, 2016.

[42] L.-W. Chen, J.-P. Tsai, Y.-C. Kao, and Y.-X. Wu, “Investigating the learning performances between sequence- and context-based teaching designs for virtual reality (VR)-based machine tool operation training,” *Comput. Appl. Eng. Educ.*, vol. 27, no. 5, pp. 1043–1063, 2019.

[43] R. de Klerka *et al.*, “Usability studies on building early stage architectural models in virtual reality,” *Autom. Construct.*, vol. 103, pp. 104–116, 2019.

[44] N. Gavish, “Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks,” *Interact. Learn. Environ.*, vol. 23, no. 6, pp. 778–798, 2015.

[45] A. Jimeno-Morenilla, J. L. Sánchez-Romero, H. Mora-Mora, and R. Coll-Miralles, “Using virtual reality for industrial design learning: A methodological proposal,” *Behav. Inf. Technol.*, vol. 35, no. 11, pp. 897–906, 2016.

[46] G. Makransky, S. Borre-Gude, and R. E. Mayer, “Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments,” *J. Comput. Assisted Learn.*, vol. 35, no. 6, pp. 691–707, 2019.

[47] H. Shen, J. Zhang, B. Yang, and B. Jia, “Development of an educational virtual reality training system for marine engineers,” *Comput. Appl. Eng. Educ.*, vol. 27, no. 3, pp. 580–602, 2019.

[48] H. Huang and C.-F. Lee, “Factors affecting usability of 3D model learning in a virtual reality environment,” *Interact. Learn. Environ.*, pp. 1–14, 2019.

[49] L. Jensen and F. Konradsen, “A review of the use of virtual reality head-mounted displays in education and training,” *Educ. Inf. Technol.*, vol. 23, no. 4, pp. 1515–1529, 2018.

[50] P. Wang, P. Wu, J. Wang, H.-L. Chi, and X. Wang, “A critical review of the use of virtual reality in construction engineering education and training,” *Int. J. Environ. Res. Public Health*, vol. 15, no. 6, 2018, Art. no. 1204.

[51] M. D. Peters, C. M. Godfrey, H. Khalil, P. McInerney, D. Parker, and C. B. Soares, “Guidance for conducting systematic scoping reviews,” *Int. J. Evidence-Based Healthcare*, vol. 13, no. 3, pp. 141–146, 2015.

[52] H. Arksey and L. O’Malley, “Scoping studies: Towards a methodological framework,” *Int. J. Social Res. Methodol.*, vol. 8, no. 1, pp. 19–32, 2005.

[53] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, “Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement,” *BMJ*, vol. 339, 2009, Art. no. b2535.

[54] C. Akdeniz, *Instructional Process and Concepts in Theory and Practice*. Singapore: Springer, 2016.

[55] A. Dengel and J. Mägdefrau, “Immersive learning explored: Subjective and objective factors influencing learning outcomes in immersive educational virtual environments,” in *Proc. IEEE Int. Conf. Teaching, Assess., Learn. Eng.*, 2018, pp. 608–615.

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