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REVIEW

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Head-mounted display-based virtual reality systems in engineering education: A review of recent research

Wen Huang[1] | **Rod D. Roscoe**[2]

[1]Engineering Education Systems and Design, The Polytechnic School, Ira A. Fulton Schools of Engineering, Arizona State University, Mesa, Arizona, USA

[2]Human Systems Engineering, The Polytechnic School, Ira A. Fulton Schools of Engineering, Arizona State University, Mesa, Arizona, USA

Correspondence
Wen Huang, Annette Caldwell Simmons School of Education and Human Development, Southern Methodist University, Dallas, Texas, 75205, USA.
Email: wenhuang@smu.edu

Abstract

Engineering education refers to developing an understanding of the principles, methods, and ways of thinking that underlie engineering, and preparing students and engineers for productive engineering careers. The purpose of this review is to explore how head-mounted display-based virtual reality (HMD VR) can contribute to these goals. Historically, engineering has not been a focus for VR in education. However, recent technical advances and decreasing prices are driving a growing public interest in applying HMD VR in this field. This article reviews 47 publications on this topic, primarily appearing from 2015 to May of 2020. The literature reveals that engineering researchers and instructors have broadly explored the potential of HMD VR in organized engineering instruction and training. However, rigorous evaluation appears to be somewhat lacking in the reviewed research, and most studies are conducted in a small-scale laboratory setting. Nonetheless, HMD VR seems to be able to motivate students to learn and it is perceived to be useful in engineering education. Researchers are recommended to explore the methods of using HMD VR to facilitate lifelong learning, especially for the retraining and reemployment of engineers who seek to change careers or collaborate with researchers in different disciplines. Engineering instructors may benefit from professional development that focuses on student-centered pedagogies and skills attuned to the latest HMD VR systems.

KEYWORDS

engineering education, head-mounted display, HMD VR, instruction, learning, virtual reality

1 | INTRODUCTION

Engineering education refers broadly to developing an understanding of the principles, methodologies, and ways of thinking that underlie engineering, and preparing students and engineers for productive careers in engineering or related fields [17,29,70]. The scope of engineering education also encompasses motivation and inclusion, such as exploring why students choose to pursue engineering [37] and supporting the participation of marginalized populations [12,22]. Thus, engineering education is driven by a variety of challenging goals, which, in turn, has inspired a long-standing quest to identify effective and innovative approaches for meeting these goals [13,16,30,36,40]—how can we efficiently recruit and prepare future generations of engineers, enhance engineers' professional skills, and disseminate engineering knowledge to the public?

The purpose of this focused review is to explore the applications, research, and potential benefits of a recent technology-based approach for engineering education—head-mounted display-based virtual reality (HMD VR). In brief, VR can be defined as a highly interactive, fully immersive multimedia environment in which the user becomes a participant in a computer-generated world [46]. This virtual world can be a simulation of a real-world environment or an imagined one. Full immersion, wherein users are mostly isolated from real-world stimuli, is a central characteristic that distinguishes VR from a desktop virtual environment (VE), augmented reality, and mixed reality. HMD VR presents the virtual images and sounds directly to the users' eyes and ears via a wearable device [65], such as the Oculus Rift [18], HTC Vive [24], or Sony PlayStation VR [62]. HMDs enable users to visually experience a three-dimensional (3D) setting (e.g., they can "look around" within the environment) while also physically navigating and interacting with virtual objects (e.g., they can "walk around" in the environment).

VR can immerse learners in a virtual world that extends or expands beyond daily life. Similar to learning in the "real world," learners interpret their virtual experiences and integrate them with existing memories to construct new knowledge [27,35,39,51]. More important, when virtual and real environments are meaningfully aligned, knowledge and insights obtained in VEs can be transferred to the real world [27]. Thus, learning in VEs can complement what students learn in physical environments.

Before the 2010s, engineering was not a mainstream focus for VR education [39]. The unsatisfactory usability of HMD VR (e.g., the headset was heavy and the resolution of display was poor) tended to hinder engineering skill acquisition [67], whereas high-end VR systems such as cave automatic VE systems (CAVEs) [31] were not affordable for most educational organizations. However, recent advances in HMD VR technology have begun to overcome these barriers. The newest generations of HMD VR significantly improve users' interactive experience in the virtual world with a quality headset at a relatively inexpensive price [27]. As a result, VR is increasingly viable for engineering education, and the research literature on these applications is expanding. Many researchers and educators are curious about the state-of-the-art application and research of HMD VR in engineering education.

There are already several recent articles reviewing the progress and possible issues in VR education research. For example, Jensen and Konradsen conducted a review of 21 papers on HMD VR education and training [27] and emphasized the impact of HMD VR on skill acquisition. Radianti, Majchrzak, Fromm, and Wohlgenannt examined 38 papers to identify the design elements of using HMD VR in higher education [55]. Although Yapp, Valentine, and Sohel had a similar focus on the current review, their primary target was virtual technology in engineering education broadly, which included HMD VR, CAVE, and desktop VE [71]. Only nine of the papers reviewed in Reference [71] were related to HMD VR in engineering education. Thus, there remains a gap in our understanding of HMD VR in engineering education that may be addressed via a more expansive and inclusive review.

The current paper aims to synthesize recent work—currently scattered across a variety of journals, conference proceedings, and unpublished theses—to better understand the applications and opportunities for HMR VR in engineering education. The primary audiences for this study are engineering education researchers and instructors who are interested in using HMD VR systems to improve or transform their pedagogy, understand how HMD VR technologies might contribute to engineering education, and/or conduct their own novel research on VR in engineering education. However, we anticipate that lessons drawn from this particular body of work will be of use and interest to broader audiences as well.

1.1 | Research questions

Previous works suggest that VR applications, including HMD VR, have broad applicability and value in education. The current review explores these applications and outcomes in the focused area of engineering education. This study is guided by several research questions:

- RQ1: How are HMD VR systems being used in engineering education? To answer this question, we consider the topics and skills (e.g., content knowledge and methodological procedures) that have been addressed using HMD VR applications, as well as related engineering education goals (e.g., increasing students' interest in engineering).
- RQ2: How are HMD VR systems being evaluated in engineering education research? To answer this question, we consider the types of studies that have assessed HMD VR outcomes and benefits. For instance, evaluations might be primarily qualitative (e.g., case studies and observations), quantitative (e.g., subjective ratings or objective learning assessments), or they might employ mixed methods. Similarly, studies could include experimental, quasi-experimental, or non-experimental comparisons. What variables and predictors have been studied? Answering these questions,

thus, characterizes the evidence base researchers can draw from, to make conclusions about HMD VR in engineering education.

- RQ3: Is HMD VR a beneficial approach for engineering education? Finally, in light of the previous questions (i.e., applications and assessments), we summarize the evidence regarding the outcomes of HMD VR applications in engineering education. What are the demonstrable advantages (or downsides) of this approach?

Across all three research questions, we also consider potential gaps—topics or goals that have not been explored, potentially useful evaluations that have not been conducted, and areas where more (or stronger) evidence is needed.

2 | METHOD

2.1 | Preliminary search

A preliminary search was conducted to hone search and inclusion criteria. Keywords pertained to VR technology (e.g., *head-mounted display*, *virtual reality*, *virtual environment*, *virtual lab*, and *virtual world*), engineering education (e.g., *engineering*, *education*, and *learning*), and combinations of terms from both categories (e.g., “virtual lab” and “engineering education”). This pilot search was conducted using the SpringerLink database.

Several issues were revealed. First, the term “HMD VR” was sometimes used to refer to technologies that were not actually head-mounted displays. For example, the CAVE system [34] provides a VR environment using wall projections viewed with digital glasses, which are not an HMD. The term “engineering education” was similarly ambiguous. In particular, the boundary between engineering education and science education was sometimes indistinct—engineering students must take a variety of science courses (e.g., chemistry and physics), but such courses do not necessarily focus on engineering.

On the basis of these observations, the following criteria and definitions were formulated to guide the subsequent formal search and selection process:

- Publications must include the full-text version in English;
- HMD VR immerses users in a VE that is separate from the real world and experienced via an image display headset. HMD VR does not include environments in which virtual objects are projected alongside or atop real-world objects;
- Engineering education refers to instruction, learning, and training activities embedded in an engineering-specific curriculum (e.g., college engineering courses) or the dissemination of engineering-specific knowledge to the public (e.g., K-12 summer camp). Although math and science content are relevant, they are not automatically considered to be engineering education;
- Engineering education also encompasses skill and professional development directed toward engineers or engineering students, such as promoting cognitive skills in related domains (e.g., visual scan) or teaching collaboration and teamwork strategies;
- The specific disciplines include engineering, computing, and information technologies.

Finally, initial searches revealed that articles citing “virtual environment,” “virtual world,” or “virtual lab” as keywords tended to refer web-based or desktop learning environments. Moreover, articles obtained via these search terms tended to be replicated in other searches. Thus, to simplify the search process, these three terms were removed from the protocol for the formal search.

2.2 | Formal search and selection process

The formal database search task was conducted at a large public university in the Southwest United States (with substantial library resources) in May 2020. The search terms again included combinations of keywords related to HMD, virtual reality, and engineering education. Diverse databases were consulted, such as Science Direct, ProQuest, Ei Compendex, SpringerLink, Taylor & Francis, Wiley, and the American Society of Engineering Education (ASEE) Conference Proceedings Search. The process followed for the literature review is shown in Figure 1. The initial search returned 1480 results. These records were screened to assess whether they met the aforementioned search criteria. When the criteria were unclear, the full text was reviewed to make the final determination. This process resulted in 46 initial publications. Next, backward and forward citation search methods (e.g., via Google Scholar functions) were used to explore articles cited in or cited by the collected works, respectively. This process revealed another 15 articles that met the criteria. Finally, 14 articles were removed when they described the same studies that had been more fully described in other articles. In total, 47 articles were included for this review.

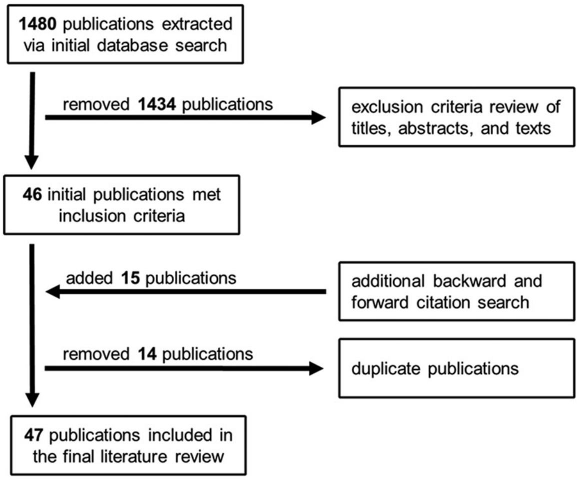

FIGURE 1 A summary of the literature review process

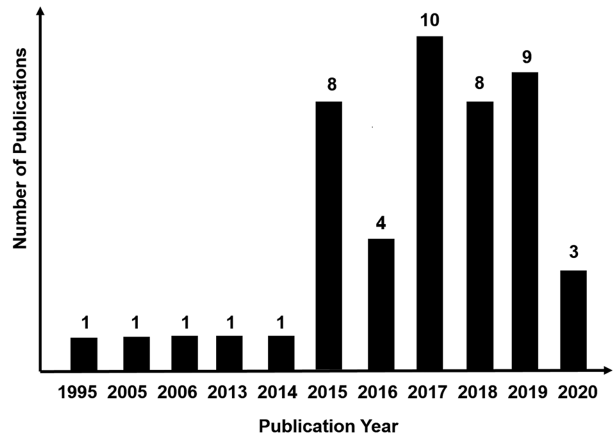

FIGURE 2 The number of relevant head-mounted display-based virtual reality publications per year

2.3 | Descriptive summary

Among the 47 selected articles, 13 were published in peer-reviewed academic journals (spanning 12 different journals), 31 appeared in peer-reviewed conference proceedings (spanning 19 different conferences), and three were unpublished graduate student theses. Figure 2 depicts the distribution of the 47 selected papers by year. It is worth noting that the number of publications has increased substantially after 2014. This pattern is aligned with the release of the Oculus Rift Development Kit 2 in the fall of 2014, which is regarded as a large step toward the formal use of the new generation of HMD VR systems 2 years later [18].

3 | RESULTS

3.1 | How are HMD VR systems being used in engineering education?

The diverse goals and purposes of engineering education were reflected in the range of applications observed for HMD VR. Across the reviewed studies, 24 focused on instruction and training of content knowledge, 11 addressed related strategies and skills, and six examined how HMD VR could motivate or inspire engineering careers and choices.

3.1.1 | Curriculum instruction

The most commonly observed use for HMD VR in engineering education was as a teaching tool for students to develop core content knowledge. Researchers leveraged the 3D modeling, simulation, interactivity, and visualization capabilities of HMD VR (along with financial cost) to teach students about a variety of domains, such as chemical and electrical engineering, construction, safety, and data visualization. As seen in other VR applications [39], educators also took advantage of HMD VR to grant students access to otherwise impossible, inaccessible, or dangerous environments.

Chemical and electrical engineering was addressed in studies to help students conceptualize dynamic, micro-level phenomena. Specifically, VR was used to present the mechanism of catalyst decay in chemical reactions [7] and the atomic structure of materials for microelectromechanical systems [54].

Another domain represented in the literature was construction and engineering design education. VR environments directed students toward deep learning with virtual design models. Application approaches included freely navigating throughout a virtual architecture design [4], disassembling and assembling a visual building model [14], sharing an understanding of a building's features with other participants [14], dynamically displaying the phases of building construction [6], and enhancing students' creativity in design [28].

A third consideration for engineering education instruction was safety. HMD VR allows students to explore simulated hazards that cannot be implemented or experienced in the real world. These simulated scenarios included virtual tunnels for training miners to identify possible hazards [19,26], a radiation experience for nuclear engineering beginners [20], an industrial plant for field operators to identify and overcome hazards or accidents in industrial processes [58], the sites of past construction accidents for teaching how to identify hazards and operating procedures [50], and practical sections for construction safety education [34].

Next, engineering education can entail equipment that is expensive to purchase, use, or maintain with HMD VR technologies. Researchers have explored a virtual industrial robot simulation for operation skill training [11] and used an animated 3D atlas model to present biomedical engineering knowledge [21]. Likewise, HMD VR environments have been created to simulate a bank IT system [41], a customer service support system [38], an astronaut system [32], and the metro system for rehearsing the emergency exercise [33].

VR also enables engineering students to visit laboratories or remote places. These types of simulations took the form of a virtual laboratory addressing fluid flow in porous media [68], a remote solar thermal power plant [9], a photovoltaic laboratory [57], an industrial plant of a tank for learning the cascade control technique of industrial processes [52], and a virtual riverbank that allowed students to measure river flow with different virtual instruments [10].

Finally, researchers and instructors have considered the potential of VR to visualize and facilitate understanding of complicated data. For instance, VR visualizations were used to assist novice software programmers to better comprehend the structure of program code [44,45].

3.1.2 | Cognitive and skill training

In several studies, HMD VR technologies were used to support the development of more general or engineering-related skills and strategies. Such studies were primarily exploratory. Perhaps the broadest application of HMD VR in engineering-related skill training was virtual assembly and manufacture. The virtually assembled objects shown in the literature included a turbine system [64], an automotive system [53], manufacturing systems [5], an airplane wing [15], industrial objects on a bus assembly line [3], pneumatic circuits [48], and medical devices [23]. It was expected that learners could not only master the skills of assembly and manufacture but also gain familiarity with concepts related to the assembled or manufactured systems during the training process.

In addition, HMD VR also has been used to train computational thinking skills [49], online engineering design [8], and visual scanning strategies [56]. Researchers predicted that HMD VR could help engineers to solve complex interdisciplinary problems and collaborate in international teams [60].

3.1.3 | Motivation

Another fundamental goal of engineering education has been to address the shortage of engineers, along with the challenges of recruiting and retaining diverse students. In a recent study, HMD VR has been involved in innovating new methods and pedagogies for motivating young persons to choose STEM careers. Relevant cases include using colorful VR constructional models to motivate high-school and undergraduate students' interest in civil engineering [14] and using purposive VR game production to motivate senior students to pursue STEM careers [66].

Researchers also applied gamified VR applications in computer science education to attract the interest of students, especially women, in STEM. Various game elements have been implemented to offer students a different and engaging mode to appreciate software programming. These innovations include a software development environment using interactive 3D blocks to replace coding [47], an embodied programming game that could create a danceable virtual metaphor after successful programming [49], visual games for understanding the code structure in a software program [43], and a programing language that could develop intelligent avatars for answering users' spoken questions [42].

3.1.4 | Summary

Available studies have demonstrated that HMD VR can indeed assist in addressing challenges in engineering instruction or training. Specifically, HMD VR has enabled engineering instruction content, equipment, or scenarios that might be invisible, dynamic, too expensive, or too dangerous in the real world. A few studies have illustrated how researchers have attempted to use HMD VR systems to support cognitive and skill training programs. Such training applications could extend classroom instruction beyond subject matter content to support the professional development of students and engineers. As an effective tool, HMD VR was also used to motivate students' interest in engineering disciplines and careers. A common method is the gamification of VR instruction or learning applications.

3.2 | How are HMD VR systems being evaluated in engineering education research?

The nascent role of HMD VR in engineering education was exemplified by the manner in which HMD VR applications were (or were not) evaluated in the literature. Of the 47 publications included in this review, only 32 sources reported one or more empirical evaluations of the educational potential of HMD VR (i.e., as opposed to merely describing a technology or hypothesized benefits).

A total of 36 evaluations were reported across the 32 publications (see appendix). The majority of these evaluations (26 studies) included university students, whereas five studied K-12 populations, three included adult employees, five included instructors and/or researchers, and one did not clearly report. The above publications included two studies with participants from two population groups and one study drawing from three population groups. Also, 27 of the evaluations were conducted in lab settings, eight occurred in field settings (e.g., classrooms and workshops), the remaining one is an online survey. All but three evaluations reported the sample size. The average sample size was about 34 participants ($M = 33.55$, $SD = 27.68$), with a broad range from 2 to 150 participants. Only 18 studies clearly reported the duration of the evaluation activities, which ranged from 5 min to 15 weeks. For the 13 laboratory-based evaluations, the average duration was about 34 min ($M = 32.18$ min and $SD = 38.04$ min). Two of these 13 evaluations required more than 40 min to complete their experiments for each participant. For the five field programs, participants engaged in VR activities over a span of about 6 weeks ($M = 5.88$ weeks and $SD = 5.00$ weeks, 1 week = 5 workdays).

3.2.1 | Types of evaluations

Among the 36 evaluations, 10 evaluations compared the effectiveness of an HMD VR system with another environment or technology (i.e., desktop VE, CAVE, mobile platform, or real-world) using random assignment to experimental and control groups. Four evaluations examined relied upon single-group or quasi-experimental designs in which no control group was provided or comparison groups were nonequivalent (e.g., groups differed in age or prior disciplinary knowledge). There were 22 evaluations that were neither experimental nor quasi-experimental in design.

Furthermore, nine evaluations primarily adopted qualitative methods in data collection and analysis, 14 adopted quantitative methods, 12 adopted mixed methods, and the method in one evaluation is not clear. Figure 3 shows the data collection methods used in these evaluations. Common qualitative methods included behavioral observation in real time [4,21,49,61,69] or with video recording software [56,60], interviews and focus groups [21,25,26,42,43,49,60], open questions in survey [7,8,41,57,61], and case studies [59,66]. Quantitative data tended to include task completion time [5,8,23,41,43–45], survey ratings [1,3,4,6–9,14,23,33,41,44,47,49,51,64,69], and exam scores [2,23,43,45,49,51,56,58] to assess participants' performance and the effectiveness of HMD VR systems.

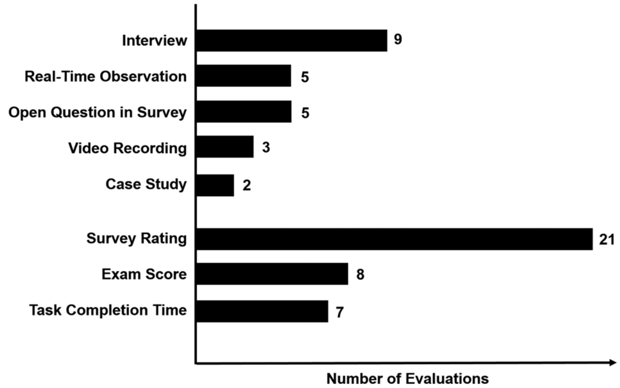

FIGURE 3 The number of evaluations for each data collection method

Figure 4 shows the data analytic methods used in these evaluations. Many evaluations reported only descriptive statistics [1,2,4,5,9,14,23,43–45,57]. Other data analytic methods included t-test and χ^2 test [6,33,64], analyses of variance (ANOVAs) or multivariate ANOVAs (MANOVAs) [49,56], correlation analysis [56], regression [61], content analysis [25,49], video, or observation analysis [56,59,63,66,69]. Due to relaxed sample size requirements, two evaluations reported Mann–Whitney U tests in group comparisons [8,41]. Notably, these were also the only studies that collected repeated measurements over time, but in-depth longitudinal analyses were not reported. Finally, there are also evaluations that did not clearly state their data analytic method or process [3,7,21,26,42,47,60].

3.2.2 | Commonly assessed variables

A variety of outcomes were assessed, including learning outcomes, motivational factors, and relevant skills (see

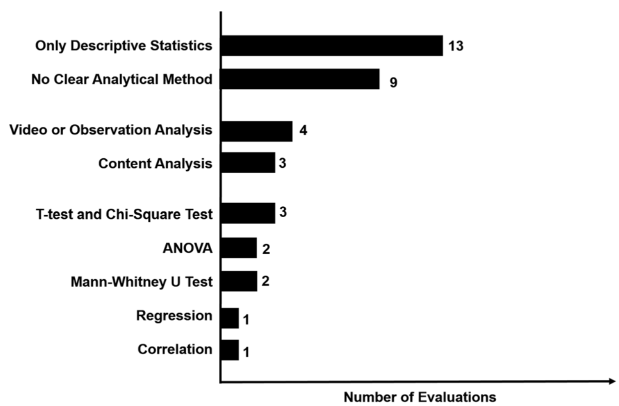

FIGURE 4 The number of evaluations for each data analytic method

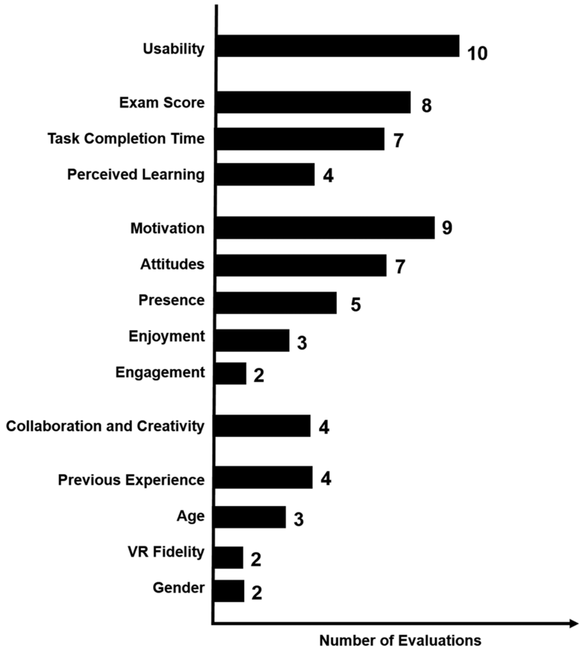

FIGURE 5 The number of evaluations for each assessed variable

Figure 5). In general, usability is the most frequently assessed factor in these articles. Ten studies did assessment in this aspect [3,9,21,25,42,47,49,61,64,69]. Higher usability and positive user experience are important qualities of a welcomed product, whereas poor user experience can reduce productivity and push users away from using the tool. With regard to learning, several studies explored overall effectiveness, referring to whether participants successfully learned the target knowledge or skills. The measures can be objective or subjective: task completion time [5,8,23,41,43–45], exam score [2,23,43,45,49,51,56,58], perceived learning, effectiveness, and efficiency [23,25,41,61].

Several studies examined whether participants reported motivation to use the technology or learn the material [4,21,41,43,45,49,57,59,66] or their engagement (i.e., mental involvement and investment in the HMD VR environment and tasks) [41,60]. A handful of studies explored whether participants experienced a sense of presence via the HMD VR—a feeling of being immersed in a meaningful, interactive world [26,49,60,61], and enjoyed this VR experience [6,23,59]. Several studies evaluated participants' attitudes toward VR, the training, course, or discipline [1,49,60]; that is, the evaluations assessed whether the HMD VR experience led participants to feel more positive toward their learning experiences and/or the subject matter.

In addition, there are studies that examined the development of participants' abilities outside of learning or motivation. Two studies examined participants' collaborative abilities in problem-solving [60,66]. The remaining study examined students' creativity (e.g., exploration and novelty) in computer programming after learning in a VR environment [49]. Several other variables were occasionally included as moderator variables to test whether the purported benefits of HMD VR were stronger for certain populations. Variables of this kind included the fidelity of the VR application [15,56], participants' gender [49,64], age [25,49,60], previous video game experience or discipline experience [60,64], and previous VR experience [14,25].

3.2.3 | Summary

Slightly more than two-thirds (68.09%) of all reviewed articles evaluated the potential of HMD VR systems in engineering education. University students were the most common participants, and researchers preferred experimental or nonexperimental designs with quantitative and mixed methods in data collection and analysis. One challenge is that several evaluations reported only descriptive statistics or did not clearly describe their analytical method (see Figure 4). Commonly assessed variables could be categorized into the system's usability, participants' cognitive achievements, and their subjective reactions. Some variables served as moderator variables to analyze the strength of HMD VR on special population groups in these studies.

3.3 | Is HMD VR a beneficial approach for engineering education?

In the previous section, we characterized the evidence base, which revealed that a number of evaluations did not include sufficient information in their data collection and analysis to offer strong conclusions. Nonetheless, the available literature suggests that HMD VR can have value for learning and engagement. In the following sections, we focus on these possible outcomes of HMD VR learning.

3.3.1 | Evidence for learning and skills

In general, the method of interaction between the learner and VR partially determines the effectiveness of an HMD VR system for learning. In most cases, HMD VR was more helpful in improving students' concept and skill learning than the desktop VE when the learning activity involved motion tracking. This benefit was demonstrated by higher posttest scores [2,23,49] or a faster task completion time [8]. If learning tasks did not involve continuous motion- or operation tracking, HMD VR was less likely to offer additional learning benefits than comparison settings. These applications include a game that only allowed the player to click buttons to control the application [41] and an application that used visualization to help novice programmers understand the structure of codes [43,44]. It is worth mentioning that individuals might have difficulties when navigating a VR environment for the first time [45,60], which might lead to a longer task completion time than the control group in the physical world, even when using motion tracking [5]. Fortunately, these initial challenges can fade away gradually [60].

3.3.2 | Evidence for interest and participation

Due to novelty, many learners expressed high interest and excitement in learning with VR [21,49,57,59,69]. They felt that this learning method was more attractive than traditional lectures [21] or a desktop VE environment [49]. This experience also increased their interest and confidence in corresponding STEM disciplines [45,49,66]. Furthermore, audiences showed higher interest in and approval of VR models than physical models when they reviewed students' architecture simulations [4]. Nevertheless, there were two exceptions where HMD VR did not show a motivational advantage over desktop VE. First, when a learning activity required physical actions, VR environments that lacked motion tracking did not show a motivational advantage (for K-12 students) as compared with a desktop [49]. Second, when the operations of a VR application were nearly identical to a desktop version, professionals in the VR environment did not show higher motivation toward play and learning knowledge than the desktop environment [41].

3.3.3 | Students' experiences and perceptions

VR environments afforded students a sense of presence [49,60], behavior control [33], and flow [60]. Students also enjoyed the VR learning experience [23,59]. In particular, when the VR educational application involved motion tracking, they reported a more positive experience [23]. Participants also thought it was easy to use VR applications to learn knowledge and skills [8,23,33].

Most VR educational applications in the reviewed literature were developed by engineering educators and were still undergoing continuous improvement. Overall, the feedback gathered about the usability of these self-developed applications was positive [3,9,21,25,42,49,64]. In addition, participants also provided feedback to help educators identify aspects to be improved: user interaction [9,21], overall usability [3], content details [21], visual representation [47], application design [49], and computing method [42]. Only one commercial VR educational application was addressed in a usability assessment, which obtained high usability ratings from students, regardless of the high-end or mid-range format [69]. There was no significant difference between HMD VR and CAVE in the usability of displaying 3D models for searching tasks [61].

The usefulness of VR educational applications was confirmed by different user groups, which included K-12 students [14], university students [7,57], high-school teachers [25], and faculties [6,26]. Users felt VR could help learners achieve learning goals more effectively [6,23,25,26] and efficiently [23] than traditional lectures. The perceived effectiveness of presenting 3D models was similar between HMD VR and CAVE [61]. Participants were satisfied with the learning experience [49] and had a positive attitude toward the use of VR in engineering education [60]. Finally, when students talked about their preferences, they mentioned more realistic interactions [8,60] and instant feedback [60] in VR. Gamification was welcomed but not necessary [60]. Students also thought that VR was more suitable for deeper learning [25].

3.3.4 | External moderators

Display fidelity is a factor that we should consider when determining whether or not to use HMD VR in engineering education. It was viable to use HMD VR in a moderate-scale assembly training, whereas introducing HMD VR into large or small-but-detailed assembly tasks might be challenging for the complexity of VR application development [15]. VR training systems had the highest training efficiency when the visual complexity of the VE matched the assessment condition [56].

Age may impact users' adoption of HMD VR. Young adults might adopt VR technologies and environments faster than older users [25,60]. Nevertheless, the concerns of older users could diminish after being in a VR environment for a few minutes [60]. Among middle-school students, older students performed significantly better than younger students during VR learning [49]. Notably, gender does not appear to impact the effectiveness of HMD VR training [64].

Individuals with more game experience could more easily navigate with an avatar in a VR environment, and those with previous experience in training and coaching were more efficient at instruction in a virtual world than inexperienced individuals [60]. However, previous game experiences did not influence the perceived usability of applying VR in instructing engineering concepts [64].

In contrast, previous VR experience significantly impacted students' perception of VR in learning. Students who previously used high-end VR equipment showed a more positive attitude toward accepting VR technology than those who had tried lower cost HMD VR systems [25]. However, students with prior VR experience did not perceive that VR could improve the understanding of concepts as much as students were using VR for the first time [14].

3.3.5 | Summary

Overall, HMD VR has the potential to enhance students' learning achievements in the engineering education field. Its effectiveness was influenced by several factors, which included but were not limited to the method of interaction, simulation realism and fidelity, and VR training time. HMD VR learning activities were interesting and welcomed by the engineering education community. Most users had a positive attitude toward VR learning and provided helpful feedback to VR applications that were in the the development stage.

4 | DISCUSSION

Educators and researchers have broadly explored the potential of using HMD VR in the area of engineering education and training. These applications include addressing challenges in the engineering curriculum instruction, enhancing students' cognition and skills through various VR training programs, and increasing students' interest in STEM careers. In particular, some specific application fields, such as safety education, assembly training, and virtual laboratory, have already matured. It is clear that using HMD VR in engineering education has been a hot topic in the VR education research and application field in recent years. This is in line with the current situation of VEs in engineering education [71], but largely different from VEs in engineering education 10 years ago when engineering simulation was constrained by the personal computing technology [39]. Considering that the HMD VR technology is still developing rapidly, the flourishing of HMD VR in engineering education will likely continue in the near future.

There is room for improvement in the evaluation procedure for reviewed studies. This is consistent with the current situation of HMD VR in higher education [55] and VEs in engineering education [71]. Quantitative and mixed methods are the primary research methods. The average duration is approximately 30 min per participant for laboratory experiments working in individual sessions, which suggests that VR studies are commonly inefficient. This inefficiency may explain why no reviewed evaluation had more than 150 participants. Many studies applied mixed methods to address the smaller sample size. However, qualitative analyses in several mixed methods articles were simplistic [7,41,43,60] — they were not able to reach the goal of strengthening quantitative conclusions in an HMD VR education study. In addition, most of these studies were conducted in the laboratory setting and many of their evaluations focused on system usability. This trend is in line with HMD VR in higher education [55] and suggests that more work is needed on using HMD VR in authentic, large-scale engineering instruction.

HMD VR systems are a valuable tool to support engineering education. This is not only due to their capability of presenting information beyond the boundary of the naked eye, but also their distinctive technical affordances (e.g., motion tracking, immersion, visualization, and rich interactions). These characteristics enable engineering education activities to be attractive and intuitive in a VE. Students are motivated to learn engineering and perceive their VR learning experiences as useful. Thus, HMD VR has the potential to maintain and even increase students' interest in engineering. HMD VR is useful to solve the issue of attrition in engineering majors. However, consistent with prior similar research works [27,71], whether adopting VR in engineering instruction and training does not directly determines students' learning achievements. In other words, VR is not a panacea for learning. It is still not clearly known why HMD VR is suitable for a specific learning task but not for another one. Only some patterns are found based on the induction of previous studies. For example, HMD VR system may be helpful for learning when the learning activity involves motion tracking and not just static observation. This is in line with a prior research on HMD VR in education and training [27].

4.1 | Recommendations for researchers

Although researchers have explored the application of HMD VR in many aspects of the engineering education domain, their focus is mostly the organized activities of instruction and training in universities or the engineering industry. However, lifelong learning is increasingly important in the modern society. Rapid developments and shifting economic factors (e.g., increasing automation, issues of sustainability, remote and online learning, and even public health crises) result in thousands of engineers needing new skills or new employment. As HMD VR can simulate workplace scenarios, and the barriers of peer coaching and collaboration in HMD VR environment are low [60], it is possible that HMD VR can support engineers' self-directed learning. To realize this goal, future studies might consider integrating HMD VR-supported engineering training courses with a personalized learning function. The training content will address the requirement of learning most up-to-date technical knowledge and skills "at home".

Furthermore, collaborations between engineering researchers and social science experts are important and necessary. HMD VR in engineering education is a research direction that requires interdisciplinary knowledge. Engineering researchers have expertise in engineering domains, whereas social science experts can contribute deep knowledge of effective pedagogy, interaction design, and evaluation. This collaboration may enhance the quality of application assessment, speed up the improvement of VR applications, and maximize applications' potential in instruction.

4.2 | Recommendations for engineering instructors

Many engineering instructors have shown high interest in HMD VR education [1,21,25]. However, instructors may wish to be cautious and begin their attempts in collaboration with developers and researchers. Research on using HMD VR in engineering education is still new and the potential of HMD VR in engineering education is not completely clear; thus, there is great value in educators and researchers working together to refine the appropriate features, functions, and design of HMD VR learning applications. In addition, using HMD VR in engineering education imposes additional demands on instructors' time and skills. VR allows students to learn in a 360-degree interactive method and environment, which may introduce new pedagogical challenges and opportunities than more familiar learning methods. Some applications even require or allow instructors and students to collaborate in the VE together [3,9,48]. Therefore, engineering instructors who have an interest to adopt HMD VR should explore the pedagogies of student-centered instruction and develop skills specifically related to operating complicated HMD VR applications.

5 | CONCLUSION

This paper reported a review of 47 publications related to HMD VR in engineering education from diverse databases. The present applications of and research on HMD VR in engineering education demonstrate similar patterns as VR and VEs in education more broadly. HMD VR has been used to solve instructional challenges, enhance students' cognition and skills, and motivate students' interest in STEM. Most studies do not include rigorous evaluation work and are still in the stage of a small-scale laboratory experiment. HMD VR-supported activities have the potential to enhance students' learning achievement and motivation, and most students and instructors perceive these activities as useful in engineering education. HMD VR learning is recognized as an effective solution for the attrition issue in engineering majors. Researchers are suggested to explore the potential of using HMD in self-directed learning for engineers' re-employment. Researchers are also recommended to collaborate with more interdisciplinary teams to conduct rigorous studies in the future. Engineering instructors are advised to explore and adapt their curriculum design and technical skills to take advantage of unique HMD VR affordances in instruction.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

Data are available on request from the authors.

ORCID

Wen Huang http://orcid.org/0000-0002-9155-0547
Rod D. Roscoe https://orcid.org/0000-0001-8327-4012

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AUTHOR BIOGRAPHIES

Dr. Wen Huang is currently a postdoctoral fellow in the Simmons School of Education and Human Development at Southern Methodist University, USA. He received his PhD degree from the Engineering Education Systems and Design program at Arizona State University, USA, in 2020. His research focuses on using immersive technologies in learning and education. He is particularly interested in modeling and longitudinal evaluations.

Dr. Rod D. Roscoe is an Associate Professor of Human Systems Engineering in the Polytechnic School of the Ira A. Fulton Schools of Engineering, and a Diane and Gary Tooker Professor of Effective Education in STEM at Arizona State University, USA. He is affiliate faculty of the Mary Lou Fulton Teachers College, the Center for Gender Equity in Science and Technology (CGEST), and the Center for Human, Artificial Intelligence, and Robot Teaming (CHART). His research investigates how the intersection of learning science, computer science, and user science can inform effective and innovative uses of educational technologies. He is also interested in how cognitive, metacognitive, and motivational learning processes can be scaffolded by educational technology.

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APPENDIX

TABLE 1 An overview of evaluations in research studies

Research studies	Setting	Participants (number/experimental time per person)	Types of evaluation	Research design/data collection/analytical method	Assessed variables	Moderators
[1]	Online survey	Instructors (30)	Nonexperimental	Quan/survey ratings/descriptive statistical analysis	Awareness of VR, willingness to use, the barrier	
[2]	Lab	Undergraduate students (48/20 min)	Experimental	Quan/exam/descriptive statistical analysis	Cognitive skills	
[3]	Lab	Undergraduate students	Nonexperimental	Quan/survey ratings	Usability	
[4]	Classroom	Undergraduate students (15/6 weeks)	Quasi-experimental	Mixed/survey ratings, observation/descriptive statistical analysis	Affective appraise, artifact evaluation	
[5]	Lab	Undergraduate students (27/15 min)	Quasi-experimental	Quan/clock/descriptive statistical analysis	Assembly time	
[6]	Lab	Undergraduate students (22)	Nonexperimental	Quan/survey ratings/*t* test	Perceived effectiveness, enjoyment, integrate with other courses	
[7]	Classroom	Undergraduate students		Mixed/survey ratings, open questions in survey	Perceived usefulness	
[8]	Lab	Undergraduate students (54/15 min)	Experimental	Mixed/survey ratings, open questions in survey, clock/Mann–Whitney *U* test	Task completion time, usefulness, ease of use	
[9]	Lab	Undergraduate students (30)	Nonexperimental	Quan/survey ratings/descriptive statistical analysis	Usability	
[14] Case 1	Lab	Undergraduate students (30)	Nonexperimental	Quan/survey ratings/descriptive statistical analysis	Intuitiveness	Prior knowledge
[14] Case 2	Classroom	K-12 students (42)	Nonexperimental	Quan/survey ratings/descriptive statistical analysis	Usability	
[14] Case 3	Classroom	K-12 students (14)	Nonexperimental	Quan/survey ratings/descriptive statistical analysis	Perceived useful	
[15]	Lab	Researcher	Nonexperimental		Usability	Fidelity

(Continues)

TABLE 1 (Continued)

Research studies	Setting	Participants (number/experimental time per person)	Types of evaluation	Research design/data collection/analytical method	Assessed variables	Moderators
[21]	Lab	Undergraduate students, instructors, professionals (150)	Nonexperimental	Qual/observation, interview	Usability, motivation	
[23]	Lab	No description (30/140 min)	Experimental	Quan/survey ratings, clock, performance score/descriptive statistical analysis	Effectiveness, efficiency, confidence, enjoyment, comfort, completion time	
[25]	Lab	Undergraduate students, instructors, researchers (25/30 min)	Nonexperimental	Qual/interview/grounded theory	Usability, effectiveness	Prior experience
[26]	Lab	Instructors (5)	Nonexperimental	Qual/Interview	Usability	
[33]	Lab	Undergraduate students (60)	Nonexperimental	Quan/survey ratings/*t* test	Ease of use, behavior control	
[41]	Lab	Undergraduate students and professionals (30/40 min)	Experimental	Mixed/survey ratings, open questions in survey, clock/Mann–Whitney U test	Engagement, motivation, performance, perceived learning	
[42]	Lab	Undergraduate students (10/30 min)	Nonexperimental	Qual/interview	Usability	
[43]	Lab	Undergraduate students (6/500 s)	Quasi-experimental	Mixed/interview, clock/descriptive statistical analysis	Effect (error rate, completion time), fun, intuitive, understand	
[44]	Lab	Undergraduate students (2/10 min)	Quasi-experimental	Quan/clock/descriptive statistical analysis	Completion time	
[45]	Lab	Undergraduate students (14)	Quasi-experimental	Quan/clock/descriptive statistical analysis	Completion time, correct rate, motivation	
[47]	Lab	Undergraduate students (50)	Nonexperimental	Qual/interview	Usability	
[49] Case 1	Classroom	K-12 students (54/2.5 h)	Nonexperimental	Mixed/survey ratings, interview, observation/thematic analysis, summative content analysis, descriptive statistical analysis	Computer Science Perceptions, Telepresence, Social presence, Usability, satisfaction, and enthusiasm	

TABLE 1 (Continued)

Research studies	Setting	Participants (number/experimental time per person)	Types of evaluation	Research design/data collection/analytical method	Assessed variables	Moderators
[49] Case 2	Classroom	K-12 students (90/1 week)	Quasi-experimental	Mixed/survey ratings, open questions in survey, knowledge quiz/ANOVA, content analysis	Presence (Telepresence, Social presence). views on the field of computer science, cognition	Gender, age
[56]	Lab	Undergraduate students (45/90 min)	Experimental	Mixed/Video, paper score/ANOVA, video analysis, correlation	Performance and transfer of learning	Fidelity
[57]	Lab	K-12 students (44/10 min)	Nonexperimental	Qual/open questions in survey/descriptive statistical analysis	Interest, usability	
[59]	Classroom	Undergraduate students (33/14 weeks)	Nonexperimental	Qual/case study	Interest, enjoyment	
[60] Case 1	Lab	Undergraduate students (36)	Nonexperimental	Qual/focus group	Attitudes	
[60] Case 2	Lab	Undergraduate students (8)	Experimental	Mixed/survey ratings, interview, and video record	Spatial presence, flow, collaborative learning behavior	Prior game experience
[60] Case 3	Lab	Professionals (10)	Nonexperimental	Mixed/survey ratings, interview, and video record	spatial coordination, behavior, performance, attitude,	Age, game experience
[61]	Lab	Undergraduate students (20)	Experimental	Mixed/open questions in survey, observation/the GLM univariate computation, the Levene's test	Suitability, usability, effectiveness for presenting 3D models.	
[64]	Lab	Undergraduate students (26/5 min)	Nonexperimental	Quan/survey ratings/t test, χ^2 test	Usability	Gender and prior experience
[66]	Classroom	Undergraduate students (21/2 months)	Nonexperimental	Qual/case study	Motivation	
[69]	Lab	Undergraduate students (26/5 min)	Experimental	Mixed/survey ratings and observation/descriptive statistical analysis and observation description	Usability	

Abbreviations: GLM, General Linear Model; VR, virtual reality.