Design Assessment in Virtual and Mixed Reality Environments: Comparison of Novices and Experts

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Abstract: The construction industry is facing a severe shortage of skilled workforce. Higher education is challenged to develop innovative strategies to help college students develop career-specific competency and accelerate the transition from novice to expert. Technology innovations such as virtual reality (VR) and mixed reality (MR) have been successfully integrated into learning and training programs to create authentic learning experiences within simulated virtual learning environments to facilitate tacit knowledge acquisition and workplace expertise development, which traditionally takes years of empirical experience and apprenticeship training. This study aims to explore potential VR and MR interventions in construction education and workforce development. It is directed at enhancing understanding of key differences between novices and experts and how VR and MR may facilitate tacit knowledge acquisition and expertise development to address the current skills gap in the construction industry. A simulation of accessibility design review and assessment for a tiny house was conducted via VR and MR mock-ups with the participation of both student novices and professional experts to collect behavioral and perceptual data using instruments that included a think-aloud protocol, a pair of pre- and postsurvey questionnaires, and audio/video recordings. Comparative analyses were conducted, and the results indicated that student novices, despite their lack of expertise, demonstrated comparable patterns of behaviors and achieved design review outcomes similar to those of professional experts with the VR and MR mock-ups. The findings of this study contribute to the body of knowledge by providing preliminary evidence of learning affordances of VR and MR in bridging experience-related gaps and suggesting opportunities for accelerating workplace expertise development among college students via technology intervention. These findings also have the potential to inform instructional design and pedagogical approaches that integrate VR and MR technology in undergraduate construction and engineering curricula. **DOI: 10.1061/(ASCE)CO.1943-7862.0001683.** *© 2019 American Society of Civil Engineers.*

Introduction

The postrecession growth of the construction industry has featured unprecedented use of digital tools and processes in parallel with a severe nationwide shortage of skilled workers (Emerson 2018; Livorsi et al. 2017; McGraw-Hill Construction 2012). The market demand for an entirely new class of tech-savvy design and construction professionals has been created (Becerik-Gerber et al. 2012) and the supply of these highly skilled, tech-proficient workers has been quickly exhausted (Reed 2016). Traditional workforce development and training both in the classroom and on the jobsite are time-consuming and resource-intensive and, thus, are incapable of addressing the workforce needs of the industry. As the industry is embracing leaner and nimbler growth to significantly improve productivity, quality, and financial viability, the same mindset of "doing more with less" is escalating in training and workforce development as well (Reed 2016).

College programs have been important partners and major intellectual suppliers of the construction industry. However, college graduates are often criticized for their lack of practical experience and working knowledge (Brunhaver et al. 2017; Dainty et al. 2004; Wu et al. 2015), especially in emerging fields of new practices such as building information modeling (BIM) (Sacks and Pikas 2013; Wu and Issa 2014). In addition, a lack of career-specific expertise developed through collegiate education has also been suggested (Ruge and McCormack 2017; Wu et al. 2015). To tackle these deficiencies, industry employers often turn to on-the-job training and retraining in hiring and recruiting efforts. The intense resources and investment required for this type of training highlight the necessity for expediting the transformation of student novices into professional experts to meet the pressing needs of the construction industry, which may be facilitated through the use of innovative and unconventional solutions (Ruge and McCormack 2017).

As visualization technology, including virtual reality (VR) and mixed reality (MR), experiences widespread adoption and implementation (Bouchlaghem et al. 2005; Wang and Schnabel 2009; Whyte and Nikolić 2018), its potential for intervention learning and training has also been rigorously explored (Ke et al. 2016;

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Lee 2012; Pan et al. 2006; Quarles et al. 2009; Shin 2017). Built upon existing research literature, this study reviews the process of expertise development in the context of the construction industry and explores how VR and MR, as two popular technology solutions in higher education, may transform educational experience and facilitate the development of career-specific expertise among college students. The investigation is premised on a systematic understanding of factors contributing to expertise development and awareness of commonly acknowledged critical differences between novices and experts in decision-making. The research objective, however, is to find out whether such differences could be mitigated by introducing VR and MR interventions. Specifically, this study would like to investigate two research questions (RQs):

- *RQ1*: In what ways do student novices attain accessibility design review outcomes similar to professional experts in VR and MR intervened environments, despite their comparative lack of expertise?
- *RQ2:* To what extent will perceptions related to self-efficacy improvements reported by student novices compare to those reported by professional experts for generating accessibility-related design assessments after using VR and MR?

The results of the two RQs can help determine whether the use of VR and MR could possibly bridge the expertise gaps between novices and experts and lead to comparable design review and assessment outcomes despite their distinct characteristics of cognition, skills, and experiences. The findings of this study can inform educators about specific affordances of VR and MR in construction and engineering education. It could also inspire undergraduate curriculum redesign with effective VR- and MR-intervened learning activities to foster comprehensive learning experiences and, thus, accelerate skilled construction workforce development.

Background

This study is built on several educational and applied research foundations and lends itself to bring together technology, learning theory, and industry practice perspectives in discussing possible innovations in construction workforce development. This section aims to (1) identify what is missing in current higher education in preparing students for professional careers via the lens of expertise by examining what constitutes expertise and how novices develop into experts; (2) introduce what learning affordance VR and MR provide to facilitate this transition; and (3) discuss why accessibility design review and assessment with VR and MR mock-ups can be an exemplary case to explore how such transition can be designed, experimented, analyzed, and replicated.

Novices and Experts: Development of Expertise

In order for students to be successful in their careers in a changing industry, they must build knowledge and skills that they can readily adapt to address the novel, complex problems that they will encounter (Litzinger et al. 2011). In other words, this requires the development of so-called expertise. Expertise involves structuring knowledge in a domain around key concepts and principles and the abilities to access and apply knowledge to new situations via dedicated applications (Cross 2004). Understanding expertise is important because it provides insights into the nature of thinking and problem solving (Brown et al. 2000). Expertise is what differentiates experts from novices; the two represent different phases of the expertise development process (Persky and Robinson 2017; Ross et al. 2005). Bransford et al. (2000) summarized six key characteristics of experts: (1) experts notice features and meaningful patterns of information that are not noticed by novices; (2) experts acquire and organize content knowledge in ways that reflect a deep understanding of their subject matter; (3) experts' knowledge cannot be reduced but instead is "conditionalized" on a set of circumstances and reflects contexts of applicability; (4) experts are able to flexibly retrieve important aspects of their knowledge with little attentional effort; (5) experts are not necessarily able to teach others despite knowing their disciplines thoroughly; and (6) experts have varying levels of flexibility in their approach to new situations.

For college students, the accumulation of knowledge and experience is a vital part of their transformation to experts. However, the shape of learning is complex, and expertise is more than the gradual accumulation of knowledge or simply years of experience (Atman et al. 2007; Bransford et al. 2000; Chi et al. 1988). Instead, only practice performed with the intention of improving a skill, which is also referred to as deliberate practice, will lead to the development of expertise. Deliberate practice requires that the individual be highly motivated to learn and improve (Ericsson et al. 1993). The two key processes in deliberate practice are identifying which knowledge or skills need to be improved and selecting a learning approach that will lead to the desired improvements. In construction and engineering education, it falls to the instructors to design and sequence the learning experiences that will promote such deliberate practices (Litzinger et al. 2011).

While the current undergraduate engineering education in the United States effectively imparts certain types of knowledge, this system is not as effective at facilitating the acquisition of tacit knowledge that represents the technical know-how gradually developed via performing tasks in the workplace (Nightingale 2009) or preparing students to integrate knowledge, skills, and affective elements (e.g., identity formation) as they develop into engineering professionals (Sheppard et al. 2008). The consequence is that engineering graduates entering the workforce struggle to transfer what they have learned in school to what is required of them as a professional. The Carnegie Foundation for the Advancement of Teaching, an independent policy and research center committed to the improvement of teaching and learning, proposed the notion of *three apprenticeships* in response to the need for more integrative learning in professional education via the Preparation for the Professions Program and identified the elements of preparation that are necessary for preparing successful professionals in the fields of engineering, nursing, law, medicine, and the clergy (Sullivan and Rosin 2008). The three apprenticeships, which can be referred to as apprenticeships of the *head*, the *hand*, and the *heart*, include:

- *Cognitive or intellectual apprenticeship (head)*: This apprenticeship includes conceptual or intellectual training to learn the academic knowledge base of engineering and the capacity to think like as engineer. In engineering education, the cognitive or intellectual apprenticeship traditionally is emphasized in the classroom setting.
- *Skill-based apprenticeship of practice (hand)*: This apprenticeship includes the development of skilled know-how and professional judgment. In engineering education, the skill-based apprenticeship of practice traditionally is emphasized in the laboratory or workplace settings, with a focus on acquiring competency in skills and tasks.
- *Apprenticeship to the ethical standards, comportment or behavior, social roles, and responsibilities of the profession (heart)*: This apprenticeship also is referred to as civic professionalism or the responsibility of the profession to the community it serves and traditionally is part of the ethics course content.

By knowing what characterizes expertise and understanding the process of how novices grow into experts via the development of the head, hand, and heart apprenticeships, faculty will be in a better position to develop appropriate instructional strategies to target outcomes that support the development of expert-like behaviors and knowledge (Atman et al. 2007; Bransford et al. 2000). Bransford et al. (2000) also emphasized the need to create learning environments that explicitly lead students to develop conditionalized knowledge rather than leaving it to students to learn the conditions under which knowledge and skills can be applied. Another critical consideration in creating effective learning experiences for expertise development is the factor of efficiency. Research indicates that progress toward expert performance requires thousands of hours of deliberate practice (Ericsson 2009; Ericsson et al. 1993). To maximize the impact of time spent on practice and application, it is imperative for engineering faculty to design the most effective learning experiences. Creating such experiences for students desiring to enter the construction industry requires an intense commitment of resources. Emerging technologies like VR and MR help overcome some of these limitations and offer a promising and cost-effective approach to creating meaningful experiences for students.

Learning Affordance of VR and MR

As two interrelated concepts on the reality–virtuality (RV) continuum, according to Milgram and Colquhoun (1999), VR is the use of computer graphics systems in combination with various display and interface devices to provide the effect of immersion in the interactive three-dimensional (3D), computer-generated environment. MR, on the other hand, refers to the incorporation of virtual computer graphics objects into a real 3D scene (i.e., augmented reality or AR) or, alternatively, the inclusion of real-world elements into a virtual environment (i.e., augmented virtuality, or AV) (Pan et al. 2006; Wang 2009). Recently, VR and MR applications have become increasingly popular and incorporated a wide spectrum of practices across industry sectors in both public and private domains (Chi et al. 2013; Rankohi and Waugh 2013; Shin 2017; Wang et al. 2018). Specifically, VR and MR provide design and construction professionals with unprecedented opportunities to promote *design communication* (Bassanino et al. 2013; Chalhoub and Ayer 2018; Wang and Dunston 2013), *collaboration* (Bassanino et al. 2013; Du et al. 2018; Dunston et al. 2010), *quality control* (Kwon et al. 2014; Park et al. 2013), and *safety management* (Kassem et al. 2017; Li et al. 2018; Sacks et al. 2013).

An emerging and rapidly developing area of interest is the educational use of VR and MR. As a technology breakthrough, VR and MR hold the power to facilitate and transform learning and training (Akçayır and Akçayır 2017; Ke et al. 2016; Pan et al. 2006; Wang et al. 2018; Wu et al. 2013). The virtual learning environment (VLE) constructed with VR and MR not only provides enriched teaching patterns and contents, but also helps improve learners' ability to explore new concepts and analyze emerging problems. Integrated with immersive, interactive, and imaginational advantages, VR- and MR-constructed VLE builds a sharable cyberlearning space that can be accessed by all kinds of learners inhabiting the virtual community (Pan et al. 2006).

To further understand the learning affordance of VR and MR, research on how people learn suggests that learning and cognition are complex social phenomena distributed across minds, activity, space, and time (Oliver and Herrington 2010; Wenger 1998), so there is a need to plan learning settings based on meaningful and relevant activities and tasks that are supported in deliberate and proactive ways (Oliver and Herrington 2010). Mayer (2005) suggests that educators can leverage technology innovations such as VR and MR to develop and implement technology-mediated learning through supplemental verbal instruction with pictorial representations of information to create a *multimedia learning environment*. Using multiple forms of media can promote meaningful learning for several reasons since learners learn better from situations that engage multiple senses than from scenarios in which words or pictures alone are used (Mayer 2001, 2009). Simultaneous presentations with multiple senses may be better than one in certain circumstances because the learner has qualitatively different ways of perceiving information.

Based on these premises, a substantial body of research literature elaborates on learning affordance of VR and MR. Approaching the topic from the perspective of technical features, enhanced presence, immediacy, immersion, and human–computer interaction, these studies have demonstrated elevated learner engagement, self-efficacy, and improved learning outcome with authentic, active, and situated learning experiences in VR- and MR-constructed VLE. Such experiences typically facilitate the development of spatial abilities, context sensitivity, problem-solving and practical skills, and conceptual understanding and change (Akçayır and Akçayır 2017; Cheng and Tsai 2013; Dunleavy et al. 2009; Ibáñez and Delgado-Kloos 2018; Martín-Gutiérrez et al. 2015; Quarles et al. 2009; Shin 2017; Wang et al. 2018; Wu et al. 2013).

Challenges of educational use of VR and MR and their learning affordance are also reported. Usability and user experience (both technology-related and design-related), presence and interaction, cognitive overload, learner characteristics, and lack of guiding learning theories are among the most commonly discussed issues (Akçayır and Akçayır 2017; Cheng and Tsai 2013; Shin 2017; Wu et al. 2013). This research is particularly interested in addressing the challenge of understanding how learner characteristics (i.e., level of expertise) and user experience may impact knowledge attainment and skills development in VR- and MR-constructed learning environments and what learning theory can be employed to explain the learning process and outcome. Specifically, the authors explore this topic through the lens of accessibility design review assessments in the building domain.

Design Review and Assessment

Design reviews are critical to the success of a building project. They eliminate costly rework and conflicts and promote creative and innovative design and construction (Soibelman et al. 2003). Traditionally, design review and assessment are conducted via a labor-intensive and time-consuming process that involves multichannel communication and collaborative decision-making relying on a large volume of two-dimensional (2D) drafting, documentation, and costly physical mockups (Dunston et al. 2010, 2011). Typically, this process consists of multiple rounds of back-and-forth stakeholder meetings throughout the entire project life cycle due to a diversity of cultures, skills, and discipline background to ensure client satisfaction, code compliance, value engineering, constructability, operability, and maintainability (Bassanino et al. 2013).

Recently, virtual design prototypes or mockups enabled by advanced 3D modeling technology such as BIM and virtual collaboration workspace enabled by visualization and interaction technologies such as VR and MR have been increasingly used in establishing the aforementioned communication channels to support communication and collaboration during design review and assessment (Bassanino et al. 2013; Kumar et al. 2011). Virtual prototypes and collaborative workspace provide opportunities for a team of project stakeholders to navigate through the model space, truly experience design alternatives and concepts, and evaluate the design based on various criteria from numerous vantage points (Kumar et al. 2011). The unprecedented visualization enhances end user engagement in instances where team members leverage

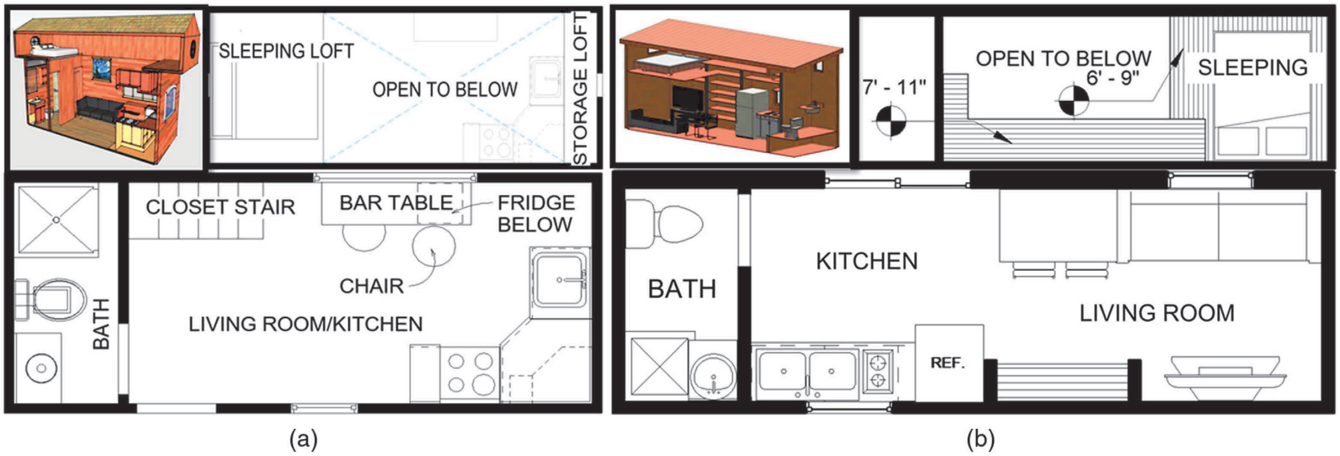


Fig. 1. Two design concepts of the tiny house: (a) Design Concept 1; and (b) Design Concept 2.

and communicate their tacit knowledge, enabling collaborative interdisciplinary participation. The interaction with the virtual environment and interaction among stakeholders situated in the design to be evaluated also empowers stakeholders with a means to conduct meaningful conversations and reconcile design perceptions by selecting any desired viewing perspective, directing and intuitively manipulating objects or conditions within the design in real time (Dunston et al. 2010). Furthermore, with distributed multiuser VR and MR framework, as suggested in Daily et al. (2000) and Wang and Dunston (2013), remote design collaboration and review are made possible, which could result in significant cost and time savings.

Admittedly, there are nontrivial technological and human behavioral obstacles to fully embracing design review and assessment in virtual environments (Bassanino et al. 2013; Wang and Dunston 2013). It is, however, foreseeable that as remote collaboration becomes more common in today's capital project delivery, the ability to communicate and collaborate in virtual workspaces so as to perform critical tasks such as design review and assessment will be desirable for the future workforce in this industry. The nature of design review and assessment necessitates the application of both head and heart dimensions of the three apprenticeships in expertise development. The research literature has shown significant divergences in strategies (e.g., schema-driven by experts versus case-driven by novices) and behaviors (e.g., problem-scoping and information-gathering efforts) between novices and experts when conducting engineering design (Atman et al. 2007; Ball et al. 2004). Therefore, this research selects design review and assessment in virtual environments as a representative use case for comparing and understanding differences between novices and experts to inform innovative strategies of developing expertise among college students with VR and MR intervention.

Method

Research Design

The core experiment of this research involved a simulated review and assessment of a tiny-house design for accessibility conducted by participants consisting of student novices and professional experts in both VR- and MR-constructed virtual environments. (This was due to the consideration that VR and MR are both popular and readily accessible to higher education. Nevertheless, it should be noted that this research did not intend to compare the two pieces of technology.) The task challenged the participants with a seemingly inappropriate question since tiny-house design is intrinsically limited to considering accessibility. Nevertheless, the intention was to create a context for critical thinking where novices and experts were deliberately applying technical knowledge (i.e., head apprenticeship) and experience-dictated professional judgment (heart apprenticeship) in problem-solving and decision-making. By probing how participants would redesign the existing tiny house according to accessibility criteria, it was possible to obtain authentic, in situ responses uniquely embedded in the virtual environments. Two similar tiny-house-design concepts (Fig. 1) were virtually mocked up in Unity 3D and then published in both VR and MR environments via the interfaces of HTC VIVE and Microsoft HoloLens, respectively. This resulted in a total of four possible virtual mockups (two for HTC VIVE and two for Microsoft HoloLens).

Participants were required to conduct design review and assessment for a randomly selected virtual mockup with both HTC VIVE and Microsoft HoloLens, guided by a graduate research assistant (GRA). With informed consent, their behavior, including movements, interactions, and comments, were recorded by the GRA with appropriate means. To further leverage the unique visualization affordances of the VR and MR environments, the MR simulation experience included participants physically navigating an actual wheelchair to support their accessibility design review and assessment. The VR environment virtually simulated physical navigation by seating participants at wheelchair height and using a point-and-click navigation approach to exploring tiny-house models. In all design review scenarios, participants were asked to verbally state what they were thinking during the activity. In addition to studying the physical behaviors observed and statements made, participants were also required to complete a pair of web-based pre- and post-survey questionnaires for feedback on the simulation experience and perceptions of the VR- and MR-constructed virtual environments. The overall research design is illustrated in Fig. 2.

Data Collection and Analysis

Since expertise is reflected in conditionalized, deliberate practices, it is necessary to observe the verbal and nonverbal behaviors of novices and experts in order to understand whether expertise had a strong impact on their decision-making process and final assessment outcomes. Interactions between participants and the virtual mockups, including verbal communication and physical exploration, constituted important indicators of tacit knowledge and types

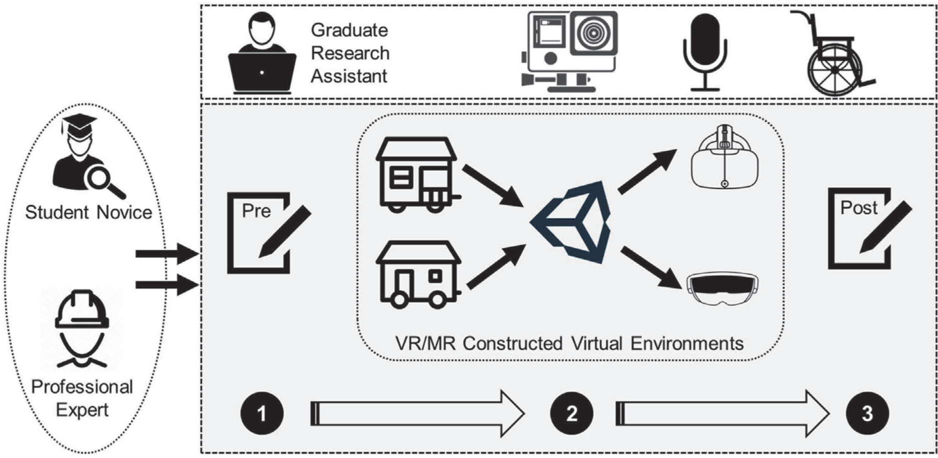


Fig. 2. Graphical overview of proposed research design.

of apprenticeships demonstrated by novices and experts. Analysis of such behavioral data could help answer *RQ1* and reveal whether VR and MR intervention provided participants with affordance in conducting comprehensive design review and assessment regardless of prior knowledge and experiences.

To facilitate participants' experience in the virtual environments to its full extent, a *think-aloud protocol* was developed. A think-aloud protocol is a tool typically used in psychology and cognitive human factors fields that has been suggested to be one of the most effective ways to assess higher-level thinking processes, which involve working memory. It establishes verbal communication of the problem-solving strategies of participants (Joe et al. 2015). In this research, the think-aloud protocol introduced participants to the experience and virtual environments they were placed in and contextualized the simulation tasks they were expected to complete. During the process, the research team used open-ended questions with regard to the experience and defined tasks to keep participants focusing on articulating *how* and *why* they made the decisions or suggestions they did. Multiple audio (i.e., Zoom H4nSP 4-Channel Handy Recorder, Hauppauge, NewYork) and video (i.e., Samsung Galaxy Tab S2 and iPad 3, San Jose, California) recording devices were deployed for capturing the think-aloud process and collecting data behavioral analysis and qualitative analysis.

To scientifically analyze and understand the audio/video data, the Behavioral Observation Research Interactive Software (BORIS) was used for coding and analysis (Friard and Gamba 2016). A behavioral coding scheme was developed to identify and quantitatively evaluate the verbalized comments and key physical interactions of the participants. By assigning codes to each identified comment or interaction, a numeric value was assigned that was later used for statistical analysis in BORIS. The coding scheme was dependent upon the experience and apprenticeship relevant to the experiment, with varied codes assigned to collect different information from the experiment. For instance, counted instances of coded elements were used for rubric-based evaluation or for comparison against different sampled groups, i.e., novices and experts in this case. An example code scheme for the accessibility design review and assessment is provided in Table 1.

To address *RQ2*, perceptual data of improved self-efficacy in accessibility design review and assessment by student novices and professional experts were collected with a pair of pre- and posttest surveys, known more generally as a repeated-measures design (Dugard and Todman 1995). The perceptual content gathered was used for statistical analysis to determine whether there was any significant change in perceived self-efficacy, tacit knowledge gains, or apprenticeship development due to the introduction of the VR and MR intervention. A main advantage of using pre- and posttest design is that the associated repeated-measures statistical analyses tend to be more powerful and, thus, require considerably smaller sample sizes than other types of analyses (Brogan and Kutner 2012).

The pretest survey questionnaire collected demographic information about the participants, including their prior working knowledge and experience with design and constructability review and visualization technology (VR and MR) used in the research activity. Self-reports of expected performance on the tasks in the experiment with different visualization technologies were also measured using five-point Likert-type scales. The posttest survey questionnaire collected data on participants' perceived experience with the design and constructability review activities in both VR and MR intervened environments. An investigation of the usability differences perceived by participants in the two environments was also integrated into the questionnaires, borrowing the 10-item attitude Likert scales, i.e., the System Usability Scale (SUS) developed by Brooke (1996). To keep data consistent, the two questionnaires were linked via the use of identifier questions to allow direct comparison of responses by the same participants before and after the

Table 1. Example behavioral codes for audio/video analysis

Code	Behavior	Data collected for statistical analysis
Countertop height	A participant comments on height of any countertop needs to be adjusted to fit the height of someone in a wheelchair	Point: a counted event
Sink types	A participant suggests a possible solution to make the sink leg-accessible	Point: a counted event
Arm interaction	A participant reaches into space to mimic touching	Point: a counted event
Navigation	Active movement by a participant in VR (click of controller and spinning of wheel chair) and MR (rolling the wheel chair) design mockups	Point: a counted event

experiment. To ensure that participants could have the best recall of the activity, the pretest questionnaire was given immediately before the experiment and the posttest questionnaire immediately after the experiment. Both questionnaires were developed and disseminated using the Qualtrics web-based survey solution for higher education. Excerpts of the two questionnaires containing only questions relevant to this paper are provided in the appendix. The full questionnaires are available from the corresponding author by request.

Results and Findings

The data collection process took place between February and May 2018 via the collaborative efforts of two institutions and active industry participation using convenience sampling. Three venues were used for data collection, including campuses of the two institutions and the 2018 Associated Schools of Construction (ASC) Regions 6 and 7 Student Competition site in Sparks, Nevada. A total of 43 participants were recruited, including undergraduate and graduate design and construction students, faculty, and industry professionals. Participants completed all physical activities and the presurvey/postsurvey questionnaires in the desired sequence, which yielded 41 valid behavioral data points (19 students and 22 professionals, respectively) and 43 pairs of filled presurvey/postsurvey questionnaires (19 students and 24 professionals, respectively).

Demographics

The demographic information summarizes profiles of the participants, including their current academic or industry undertakings, accumulative industry experiences, prior design, or constructability review experience, as well as prior working knowledge with VR and MR technology. Among the 43 participants, as shown in Fig. 3(a), there were 19 students (including 13 undergraduate seniors, 5 juniors, and 1 graduate student), 8 faculty, and 16 industry professionals in construction (11), architecture (4), and engineering (1), respectively. Students (*novices* hereafter) in general had very little industry experience, and none had accumulated more than 4 years of experience. The majority of faculty and industry professionals (*experts* hereafter) had more than 8 years' industry experience [Fig. 3(b)]. Furthermore, all experts had completed their degrees and were working in a construction-related field. As Fig. 3(c) indicates, two-thirds of the faculty and industry professionals had prior experience in design and constructability reviews that used traditional paper-based plans and specifications. Nearly half of the students also reported such paper-based experience. However, neither group had much experience with design and constructability review with VR or MR mockups. In terms of prior working knowledge with technology, both groups seemed to be more familiar with VR than MR, according to Fig. 3(d).

Behavioral Data Analysis

Behavioral data, including verbal and nonverbal communication, were collected and coded in BORIS for analysis. With the think-aloud protocol, student novices and professional experts attempted in both VR- and MR-constructed virtual environments to identify (via direct oral comments) design elements and constructability issues related to accessibility of the tiny house presented based on cognitive understanding and knowledge of accessibility design principles. This part of behavior was deemed most relevant to the head apprenticeship. Participants were also prompted to propose possible solutions based on prior experience and professional judgment, which was most relevant to the heart apprenticeship. Actions including navigation movement in the virtual environments

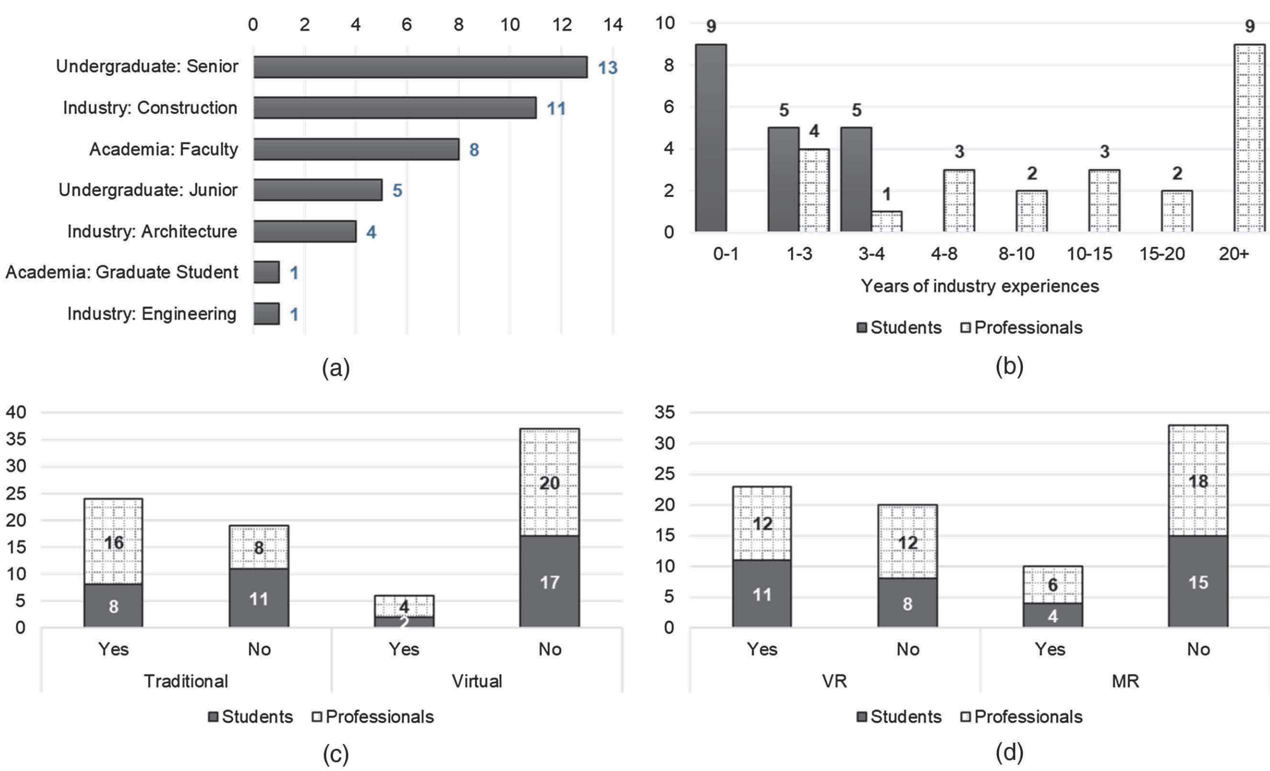


Fig. 3. Demographic information of participants, including: (a) current academic/industry role; (b) years of accumulated industry experience; (c) prior design and constructability review experience; and (d) prior working knowledge with technology.

Table 2. Coded behavioral data of novices and experts in VR and MR environments

	Behavioral data in VR environments (counts)				Behavioral data in MR environments (counts)			
Group	Issues	Solutions	Movement	Interaction	Issues	Solutions	Movement	Interaction
Novices	169	86	208	43	160	90	532	66
Experts	199	83	249	43	192	80	620	94

Table 3. Issues (VR): Independent sample *t*-test results

	Levene's test for equality of variances		*t*-test for equality of means					95% confidence interval of difference	
Assumption	F	Significance	*t*	df	Significance (2-tailed)	Mean difference	Standard error difference	Lower	Upper
Equal variances assumed	2.359	0.133	−0.165	39	0.870	−0.151	0.915	−2.001	1.700
Equal variances not assumed	—	—	−0.169	37.812	0.867	−0.151	0.893	−1.959	1.657

Table 4. Summary of independent samples *t*-tests results for all behavioral data

Intervention	Behavioral data category	*t* value	df	*p* value	Novices/experts difference
VR	Issues	−0.165	39	0.870	No significant difference
	Solutions	1.596	39	0.118	No significant difference
	Movement	−0.226	39	0.822	No significant difference
	Interaction	0.590	39	0.558	No significant difference
MR	Issues	−0.309	39	0.759	No significant difference
	Solutions	1.949	39	0.059	No significant difference
	Movement	−0.043	39	0.966	No significant difference
	Interaction	−1.248	39	0.220	No significant difference

and attempted interactions (e.g., arm stretching, propping, and quantifying visuals) with the virtual mockups were also captured. Four main categories of behaviors were recorded, coded, and counted: *Issues* (verbal), *Solutions* (verbal), *Movement* (nonverbal), and *Interaction* (nonverbal). Table 2 summarizes the behavioral data of novices and experts in both VR and MR environments.

One of the advantages of BORIS coding is that it enables quantitative analysis and interpretation of behavioral data with appropriate statistical methods. The objective of behavioral data analysis is to address *RQ1*, which aims to determine whether novices can reach accessibility design review and assessment outcomes similar to those of experts in VR and MR intervened environments despite their lack of expertise. Such a comparison is typically conducted using a *t*-test. Nevertheless, this study used two independent samples, i.e., novices and experts, with different sample sizes. The coded behaviors are translated into counts, which are numeric and discrete data. Considering these data characteristics and relatively small sample sizes (i.e., 41 valid data points), a Shapiro–Wilk test (Yazici and Yolacan 2007) was performed to determine whether the behavioral data were normally distributed and what *t*-test should be used to compare novices and experts behaviors and performances. The Shapiro–Wilk test result confirmed the normal distribution of the four categories of behavioral data collected, and the independent samples *t*-test (Kim 2015) was selected for behavioral data analysis using IBM SPSS Statistics 25.

The independent samples *t*-test was performed on all four categories of behavioral data including *Issues*, *Solutions*, *Movement*, and *Interaction*. Using *Issues* data collected from the VR environment as an example, 19 novice data points and 22 expert data points were analyzed. Table 3 presents the detailed independent samples *t*-test results. It should be noted that a Levene's test for equality of variances was embedded in Table 3 to determine which *t*-test result should be reported. In this example, since the Levene's test significance = 0.082, which is greater than 0.05, equal variances between the two samples (i.e., novices and experts) were assumed. Thus, the top row of the *t*-test results should be reported, which can be written as $t(39) = -0.165$, $p = 0.870$, where 39 is the degree of freedom (DOF). Since $p > 0.05$, there was no statistically significant difference observed between the novices and experts in identifying design issues related to accessibility. The complete independent samples *t*-test results were summarized in Table 4, showing no p values greater than 0.05, which suggests that there were no significant differences observed between novices and experts in any of the four categories of behavioral data.

A dive into the *Issues* data further revealed some noteworthy findings. Because the tiny-house design was composed of four main spaces, i.e., *kitchen*, *bath*, *living*, and *sleeping*, the accessibility issues identified by novices and experts in VR and MR environments were mapped to the space layout, as shown in Fig. 4. Apparently, the issue count distribution per space exhibited highly comparable patterns between novices and experts in both VR [Fig. 4(a)] and MR [Fig. 4(b)] environments. Furthermore, when examining the identified issues and their frequency based on the associated building elements (e.g., sink, countertop, accessories, bed, furniture, shower, and bath), novices and experts seemed to arrive at similar patterns again, according to Fig. 5. The performance consistency between novices and experts based on both quantitative and qualitative comparisons relates directly to *RQ1* and lends support to the hypothesis that VR- and MR-constructed environments could bridge the expertise gap and provide novices with meaningful affordance to achieve comparable outcomes with experts in the simulated accessibility design review and assessment.

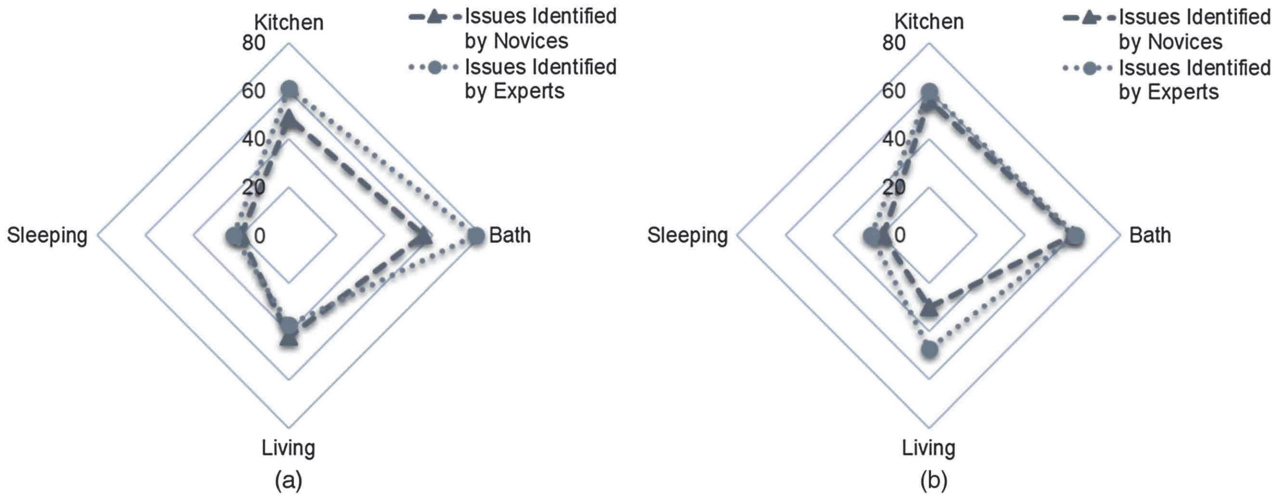


Fig. 4. Accessibility issues identified by novices versus experts: (a) issue counts per space in VR; and (b) issue counts per space in MR.

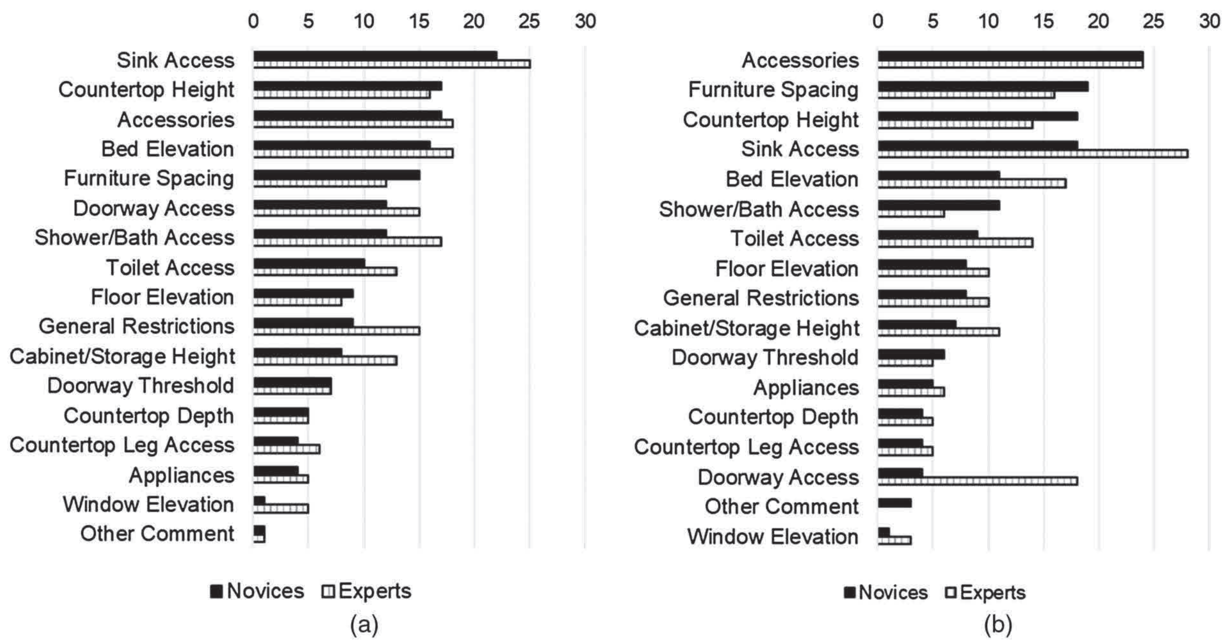


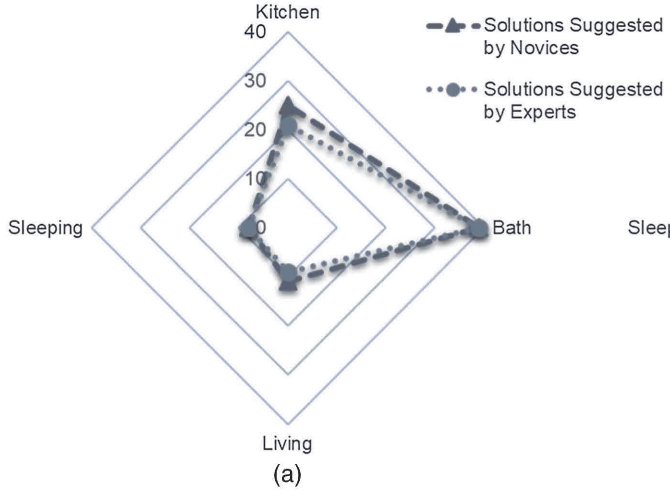
Fig. 5. Accessibility issues identified by novices versus experts: (a) issue counts per building element in VR; and (b) issue counts per building element in MR.

A similar analysis was also conducted for the *Solutions* data, where novices and experts suggested possible improvements to the existing tiny-house design to address the accessibility issues identified. The decision-making process involved in determining possible solutions was more than cognition of design elements, understanding of accessibility design principles, and building code stipulations but required professional judgment on the appropriate arrangement of physical and functional ingredients of accessibility design based on authentic understanding of users' needs and values. In other words, identifying accessibility design issues was more of a reflection on the head apprenticeship, while suggesting possible solutions was more dependent on the heart dimension of apprenticeship. Nevertheless, according to Fig. 6, within the VR- and MR-constructed environments, novices again seemed to demonstrate outcomes highly comparable with those of experts in recommending possible solutions to improve the accessibility of the different spaces in the tiny house. This finding further confirms that, despite their lack of expertise, novices could reach accessibility design review outcomes similar to those of professional experts in both quantitative and qualitative ways.

Perception Data Analysis

This research is also interested in perception changes of novices and experts via the simulation experience intervened by VR and MR. To address *RQ2*, the pre- and posttest questionnaires investigated perceptions from two different perspectives:

1. *Self-efficacy in design review and assessment*: Self-efficacy refers to the conviction that one can successfully execute the behavior required to produce the desired outcomes (Bandura 1977). The questionnaires asked the participants to self-report confidence (on a five-point Likert scale, where 1 indicates low



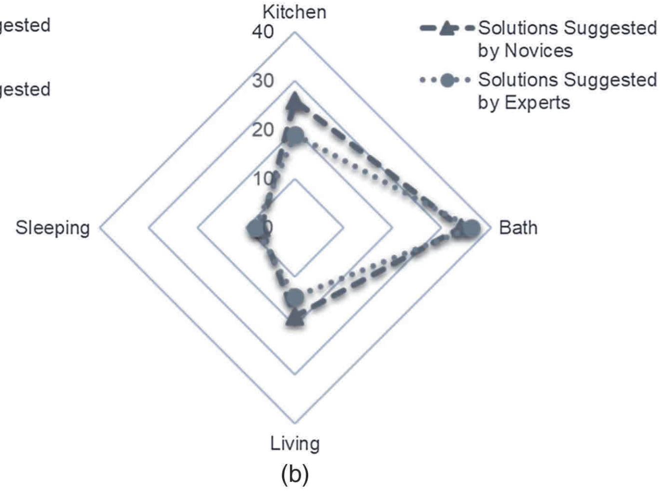


Fig. 6. Solutions suggested to improve accessibility by novices versus experts: (a) solution counts per space in VR; and (b) solution counts per space in MR.

Table 5. Paired self-efficacy data (novices): Wilcoxon signed rank test—Ranks

Design element analysis	Rank	N	Mean rank	Sum of ranks
Novices post—novices pre	Negative ranks	2[a]	9.00	18.00
	Positive ranks	11[b]	6.64	73.00
	Ties	6[c]	—	—
	Total	19	—	—

[a]Novices post < novices pre.
[b]Novices post > novices pre.
[c]Novices post = novices pre.

Table 6. Paired self-efficacy data (novices): Wilcoxon signed ranks test—Statistics

Design element analysis	Novices post—novices pre
Z	−2.027[a]
Asymptotic significance (2-tailed)	0.043

[a]Based on negative ranks.

confidence and 5 indicates high confidence) in conducting design review and assessment before and after the experiment, focusing on design element analysis and constructability analysis.

2. *Perceptions toward affordance of VR and MR technology*: The questionnaires asked the participants to rate affordance of VR and MR (on a five-point Likert scale, where 1 indicates low affordance and 5 indicates high affordance) in facilitating education and application of design review and assessment.

A total of 43 pairs (19 from novices and 24 from experts) of valid questionnaires were collected. Considering the nature of the Likert-scale data—categorical, ordinal, and not normally distributed (Allen and Seaman 2007)—two different statistical methods were selected for data analysis on self-efficacy and affordance. Specifically, for self-efficacy in design review and assessment, a Wilcoxon signed-rank test (Rosner et al. 2006) was used for the paired pre- and posttest data of both novices and experts. For the affordance of VR and MR in design review and assessment education and application, a Mann-Whitney U test (MacFarland and Yates 2016) was used to compare perceived affordance of VR and MR between novices and experts.

Self-Efficacy in Design Review and Assessment

The Wilcoxon signed-rank test was performed using IBM SPSS 25 on the pre- and posttest Likert-scale scores of self-efficacy in *design element analysis* and *constructability analysis*, which were the two major components of the simulated accessibility design review and assessment. Tables 5 and 6 present an example of the Wilcoxon signed-rank test with pre- and posttest design element analysis data by novices. The test results consist of the Wilcoxon signed-rank test ranks (Table 5) and test statistics (Table 6). Since the p-value, i.e., *asymptotic significance (two-tailed)*, is smaller than 0.05 according to Table 6, novices' posttest self-efficacy in design element analysis was statistically significantly higher than pretest ranks, with $Z = -2.027$ and $p = 0.043$. Table 7 summarizes all Wilcoxon signed-rank test results for design element analysis and constructability analysis Likert-scale score data self-reported by both novices and experts.

According to Table 7, novices perceived significant self-efficacy gains in both design element analysis and constructability analysis after the simulation experience. Experts, on the other hand, reported significant self-efficacy gains only in design element analysis. Although the mean of the posttest Likert-scale scores (4.54 out of 5) was higher than the mean of pretest scores (4.00 out of 5),

Table 7. Summary of Wilcoxon signed-ranks tests for paired self-efficacy data

Group	Self-efficacy	Z	p-Value	Self-efficacy difference significance
Novices ($n = 19$)	Design element analysis	−2.027	0.043	Posttest significantly > pretest
	Constructability analysis	−2.433	0.015	Posttest significantly > pretest
Experts ($n = 24$)	Design element analysis	−2.429	0.015	Posttest significantly > pretest
	Constructability analysis	−1.766	0.077	No significant difference

Table 8. Perceived education affordance: Mann-Whitney U test—Ranks

Group (1 = novices, 2 = experts)	N	Mean rank	Sum of ranks
1	19	21.32	405.00
2	24	22.54	541.00
Total	43		

Table 9. Mann-Whitney U test—Statistics

Test[a]	Perceived education affordance
Mann-Whitney U	215.000
Wilcoxon W	405.000
Z	−0.432
Asymptotic significance (2-tailed)	0.666

[a]Grouping variable: Group (1 = novices, 2 = experts).

there was no statistically significant difference in self-efficacy gains in constructability analysis after the simulation experience for experts.

Perceived Affordance of VR and MR in Enhancing Design Review and Assessment

Understanding perceptions toward the affordance of VR and MR in enhancing education and application of design review and assessment can be beneficial, considering a limited research literature and empirical evidence of leveraging VR and MR in learning and training intervention in this industry compared with others such as the healthcare, automotive, and manufacturing industries. Tables 8 and 9 present an example of a Mann-Whitney U test comparing perceived affordance of VR by novices and experts in educating college students about design review and assessment. The test results again consist of a Mann-Whitney test ranks (Table 8) and test statistics (Table 9). Since $Z = -0.432$ and $p = 0.666$ (>0.05) according to Table 9, there was no statistically significant difference in education affordance of VR perceived by novices and experts. Similarly, as summarized in Table 10, there was no statistically significant difference in the affordance of VR in facilitating the application of design review and assessment perceived by novices and experts. The same conclusion was applicable to the perceived education and application affordance of MR, which suggests a high uniformity of perceptions achieved between the novices and experts toward VR and MR technology based on the simulation experience in this research.

User experience could also contribute to perceived affordance of technology. In designing VR and MR intervention for education and training, user experience could play an important role in the efficiency and efficacy of such interventions. This research integrated the 10-question SUS test developed by Brooke (1996) and compared user experiences of novices and experts with both VR and MR. The SUS test consists of a series of user experience questions on a five-point Likert scale, where 1 indicates strongly disagree and 5 indicates strongly agree. Table 11 summarizes the SUS

Table 11. SUS questions and combined results of novices and experts

		Mean (out of 5)	
No.	SUS questions	VR	MR
1	I think that I would like to use (VR, MR) frequently	4.3	3.8
2	I found (VR, MR) unnecessarily complex	1.6	2.2
3	I thought (VR, MR) was easy to use	4.2	4.0
4	I think I would need the support of a technical person to be able to use (VR, MR)	2.6	2.7
5	I found the various functions in (VR, MR) were well integrated	4.1	3.8
6	I thought there was too much inconsistency in (VR, MR)	1.7	2.4
7	I would imagine that most people would learn to use (VR, MR) very quickly	4.3	4.0
8	I found (VR, MR) very cumbersome to use	2.1	2.4
9	I felt very confident using (VR, MR)	4.3	3.8
10	I needed to learn a lot of things before I could get going with (VR, MR)	1.8	2.1

Table 12. Summary of Mann-Whitney U tests for comparing user experience data

Technology	User experience	Mean	Z	p Value	Group difference (novices versus experts)
VR	Positive	4.24	−0.468	0.640	No significant difference
	Negative	1.98	−1.143	0.253	No significant difference
MR	Positive	3.86	−0.356	0.722	No significant difference
	Negative	2.37	−0.565	0.572	No significant difference

test results, and Table 12 summarizes the Mann-Whitney U tests results from comparing user experience between novices and experts in the experiment. Notably, according to Table 11, SUS used paired questions to solicit both positive (Questions 1, 3, 5, 7, and 9) and negative (Questions 2, 4, 6, 8, and 10) user experience ratings. Therefore, the Mann-Whitney U tests summarized in Table 12 were performed separately for the two groups of questions to allow for a more meaningful comparison. As shown in Table 12, there were no statistically significant differences between novices and experts with respect to their user experience with VR and MR, measured on either positive or negative scales.

Discussion and Limitation

Both novices and experts showed great interest in exploring virtual mockups in environments with VR and MR interventions. In general, student novices tended to be keen on technology and would spend some time playing with the devices before actually starting to conduct the design review and assessment tasks. In contrast, professional experts seemed to be more focused and jumped right into the activity. Experts were generally more concerned with and

Table 10. Summary of Mann-Whitney U tests for comparing perceived affordance data

Technology	Affordance	Mean	Z	p-Value	Group difference (1 = novices versus 2 = experts)
VR	Education	4.67	−0.432	0.666	No significant difference
	Application	4.49	−0.291	0.771	No significant difference
MR	Education	4.21	−0.652	0.515	No significant difference
	Application	4.09	−0.183	0.855	No significant difference

strategic in navigating and exploring the virtual environments when performing the design review and assessment. They were usually the ones who initiated and led the conversation with the GRA. Their comments and proposed solutions also tended to be better articulated and more contextual, suggesting the application of prior experience, professional judgment, and best practices in similar circumstances they might have encountered previously. The novices typically needed to be prompted by the GRA to articulate their observations, and their comments were more generic. Nevertheless, novices were very active in exploring the virtual environments and interacting with the virtual mockups. Their proposed solutions tended to be more in situ, suggesting immediate feedback from the virtual environments they were exploring and interacting with. Such observed novice behavioral characteristics demonstrate the essential role of faculty in designing an appropriate learning approach to explicitly lead students to develop conditionalized knowledge rather than leaving it up to students to learn the conditions under which knowledge and skills can be applied. In other words, achieved behavioral similarity between novices and experts in this research suggested a possible pathway to accelerate expertise development via technology intervention; yet pedagogical innovation must be conditionalized and well thought out to encourage active engagement of students with the constructed learning environment.

Current research design and data collection have some limitations. First and foremost, the convenience sampling method and a relatively small sample size could attenuate the significance of findings from the research results. Second, in this particular study, the categorization of novices and experts largely relied on self-reported profiles and industry experience. A more comprehensive qualification screening process should be developed and adopted in future research. Finally, behavioral data collection with audio/video recording devices seemed to be effective only at measuring verbal and nonverbal communications of participants, while other meaningful data reflecting the decision-making process during design review, including eye movement and focus of attention, seemed to be difficult without special devices such as eye-tracking sensors. The lack of definitive evidence and insights into how behavioral data of novices and experts could link to their integration of various apprenticeships in observation, analysis, and decision-making seemed to represent a formidable challenge to research in this field.

Concluding Remarks and Future Research

This research compared novices and experts in accessibility design review and assessment with VR and MR intervention. It investigated some critical questions to address the premises of how VR and MR might provide education and training affordance for workforce development in the construction industry. Specifically, this research revealed highly comparable patterns of behaviors and demonstrated that there were no statistically significant differences in accessibility design review and assessment outcomes between novices and experts in the VR- and MR-constructed virtual environments, despite novices' apparent lack of professional experience and expertise. This conclusion was drawn based on several statistical analyses performed with four main categories of behavioral data, which reflected both cognitive understandings of accessibility design principles and professional judgment on constructability.

The research also confirmed perceived education and application affordance of VR and MR by both novices and experts with a high uniformity. This common understanding and acknowledgment could serve as a solid foundation for holistic and collaborative planning of VR and MR adoption and implementation in the construction industry. Based on these findings, it is possible to propose innovative programs leveraging VR and MR intervention to bridge experience-incurred gaps in existing design and construction education and training, thereby accelerating the development of expertise among novices and cultivating a skilled workforce.

Future research is intended to replicate and expand similar VR- and MR-intervened learning experience to facilitate students' acquisition of other essential domain knowledge of undergraduate construction and engineering curriculum. Efforts will be dedicated to exploring all three apprenticeships, including head, hand, and heart learning in VR- and MR-constructed learning environments. By identifying appropriate use cases in current undergraduate curriculum and industry best practices, research will be conducted to advance understanding and development of VR and MR as cyberlearning technology to develop expertise among student novices and accelerate future workforce development in the construction industry. A particular area of interest will be investigating the impacts of innovative VR- and MR-intervened learning experience on underrepresented and minority students in varied institutional contexts.

Appendix. Excerpts of Pre- and Postperception Survey Questionnaires

Excerption of Pretest Questionnaire

Please list the first 3 letters of your mother's maiden name (add "x" to the end if shorter than 3)

Please list the last 4 digits of your phone number

Which best describes your current role/job function?

Please indicate your cumulative years of industry experience

Please indicate your level of agreement with the following statements (where 1 indicates strongly disagree and 5 indicates strongly agree):

- I can effectively assess design elements with a traditional set of plans and specs (1, 2, 3, 4, 5)
- I can effectively assess construction decisions with a traditional set of plans and specs (1, 2, 3, 4, 5)

Have you been involved in a design or constructability review session?

Have you been involved in a virtual design or constructability review session?

Before this survey, did you have prior working knowledge of virtual reality (VR)?

Before this survey, did you have prior working knowledge of mixed reality (MR)?

Excerption of Posttest Questionnaire

Please list the first 3 letters of your mother's maiden name (add "x" to the end if shorter than 3)

Please list the last 4 digits of your phone number

Please indicate your level of agreement with the following statements (where 1 indicates strongly disagree and 5 indicates strongly agree):

- I can effectively assess design elements that I saw during the activity (1, 2, 3, 4, 5)
- I can effectively assess construction decisions that I was presented with during the activity (1, 2, 3, 4, 5)

Please indicate your level of agreement with the following statements about your VR experience using HTC VIVE in this activity (where 1 indicates strongly disagree and 5 indicates strongly agree):

- There was enough information provided by VR to formulate my design and construction assessments (1, 2, 3, 4, 5)

- VR can be useful to teach students how to make effective design and construction decisions (1, 2, 3, 4, 5)

Please indicate your level of agreement with the following statements about your MR experience using Microsoft HoloLens in this activity (where 1 indicates strongly disagree and 5 indicates strongly agree):

- There was enough information provided by MR to formulate my design and construction assessments (1, 2, 3,4, 5)
- MR can be useful to teach students how to make effective design and construction decisions (1, 2, 3, 4, 5)

Please evaluate the usability of the HTC VIVE and Microsoft HoloLens based on your experiences in this activity (where 1 indicates strongly disagree and 5 indicates strongly agree):

- I think that I would like to use (VR, MR) frequently (1, 2, 3, 4, 5)
- I found (VR, MR) unnecessarily complex (1, 2, 3, 4, 5)
- I thought (VR, MR) was easy to use (1, 2, 3, 4, 5)
- I think I would need the support of a technical person to be able to use (VR, MR) (1, 2, 3, 4, 5)
- I found the various functions in (VR, MR) to be well integrated (1, 2, 3, 4, 5)
- I thought there was too much inconsistency in (VR, MR) (1, 2, 3, 4, 5)
- I would imagine that most people would learn to use (VR, MR) very quickly (1, 2, 3, 4, 5)
- I found (VR, MR) very cumbersome to use (1, 2, 3, 4, 5)
- I felt very confident using (VR, MR) (1, 2, 3, 4, 5)
- I needed to learn a lot of things before I could get going with (VR, MR) (1, 2, 3, 4, 5)

Data Availability Statement

Date generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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