Comparison of Building Design Assessment Behaviors of Novices in Augmented- and Virtual-Reality Environments

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Abstract: Design and construction professionals must make well-informed decisions for every project that meets both industry standards and building codes and also the specific needs of building users and clients. In order to make effective decisions, research suggests that explicit knowledge, defined as easily codified and communicated information, and tacit knowledge, considered to be the *know-how* of completing a task, must be effectively applied. While there is recognition of the need for both forms of knowledge, architecture engineering and construction (AEC) education has historically focused on covering content-related explicit knowledge in the classroom. As a result, students generally develop tacit knowledge over their careers. Due to an aging AEC workforce, there is a need to support tacit knowledge development in the classroom to enable students entering the industry to supplement the collective tacit knowledge that will exit the industry as the current generation of practitioners retires. Therefore, the authors of this paper explore the use of augmented reality (AR) and virtual reality (VR) to provide immersive virtual experiences aimed at replicating the types of scenarios that students might experience in their careers that would require them to apply tacit knowledge. The authors tasked students in construction-related disciplines with assessing a building design and making judgments about how the design should be modified to support an occupant in a wheelchair in both VR and AR. Using two similar models and a counterbalanced research methodology, the authors coded the statements and behaviors of the student participants during this design assessment exercise. The results of this work indicate that both technologies elicited statements that were indicative of explicit knowledge related to the needs of a wheelchair-bound occupant. When AR and VR were found to directly encourage physical exploration in the experience, both led to behaviors that simulated the completion of tasks that might be performed by a wheelchair-bound occupant. These behaviors were frequently followed by comments that were indicative of tacit knowledge. While this type of behavior was observed in both AR and VR, AR seemed to more directly encourage this type of interaction among participants. The contribution of this work is in providing observational evidence to demonstrate how the physical exploration affordances of AR and VR may be able to support experiences that foster the use and development of tacit knowledge related to AEC-related decision-making. **DOI: 10.1061/(ASCE)AE.1943-5568.0000396**.

Introduction

The building industry is unique from many others because it typically requires teams to create new designs for every new building project. This requires individuals in this industry to make well-informed decisions to create designs that can be effectively constructed and that also meet the needs of their eventual occupants. To make effective decisions, building industry practitioners must apply both explicit knowledge, defined as knowledge that is representative of information that can be readily articulated, codified, accessed, and verbalized (Collins 2010); and tacit knowledge, defined as knowledge that can only be obtained through experience, the *know-how* of completing a task, and is typically hard to articulate to others (Collins 2010; D'Eredita and Barreto 2006; Maravilhas and Martins 2019). While both forms of knowledge are critical to effective decision-making, educators have traditionally focused on teaching content related to explicit knowledge (Hizar Md Khuzaimah and Hassan 2012; Pathirage et al. 2008). Currently, the building industry is experiencing a shift in its workforce that is the result of an aging construction workforce that is nearing retirement (Bureau of Labor Statistics 2017; Henderson 2013). Not only does this illustrate the need for more workers, but it also highlights the collective wealth of tacit knowledge that will exit the industry in the very near future when these workers retire. Therefore, educators need to develop new and improved approaches for providing learning experiences that enable students to develop not only the traditional explicit knowledge required for their career success, but also the tacit knowledge that they will need in order to make effective design and construction decisions in their future careers. While tacit knowledge is valued throughout the industry, limited research has been conducted to understand how it may be directly introduced into building design and construction education.

In recent years, researchers have begun exploring the use of augmented reality (AR) and virtual reality (VR) for providing immersive learning experiences in a classroom environment that can simulate the physical building environment, where tacit knowledge has traditionally been developed (D'Eredita and Barreto 2006). AR superimposes virtual content on a user's view of a physical space (Hughes et al. 2005; Milgram and Kishino 1994), while VR completely replaces the physical world with a synthetic visual experience (Marini et al. 2012). While both types of environments

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may be able to simulate aspects of the physical building environment in a classroom setting, the extent to which these modes of visualization enable or hinder the development of tacit knowledge remains unclear. Therefore, this paper is aimed at understanding the ways in which AR and VR environments may elicit statements and behaviors that suggest the presence of tacit knowledge among students pursuing education for careers in the building industry.

To explore this broad topic, this work specifically tasks construction management and construction engineering students with evaluating a building design and providing design assessment related to handicap accessibility. This type of assessment requires participants to employ professional judgment in order to empathize with the eventual occupant to make decisions that ensure the overall function of a space for an individual with mobility constraints. Similarly, this handicap accessibility context challenged student participants to make empathetic judgments to identify aspects of the design that would require modification to support the needs of an occupant who was confined to a wheelchair. Students reviewed two different designs of very small houses using AR and VR. Neither design concept was created with handicap accessibility in mind. This meant that both concepts had numerous aspects of the design that could be modified to better support an occupant in a wheelchair. This methodology enabled the researchers to address the following research questions:

- How do behaviors demonstrated and design suggestions stated by students compare and contrast between these two visualization environments?
- How do the perceptions reported by student participants vary between these environments?

This work identifies the different types of design review behaviors that are elicited in AR and VR environments among students from construction-related majors. These findings illustrate the types of impacts that AR and VR may have on design assessment, specifically examining the physical engagement affordances of each that lead to the demonstration of spoken or physical behaviors related to the application of tacit knowledge. This paper contributes to the current understanding of VR and AR for education to support the development of tacit knowledge specific to building design assessment among construction students. This understanding may provide discipline-specific evidence that educators may use to create learning experiences that can support tacit knowledge development among students interested in pursuing construction-related careers.

Background

Industry Demands and Challenges

The Bureau of Economic Analysis, managed by the Department of Commerce, reports that the United States' building industry spends over $800 billion annually (Howells et al. 2019). Furthermore, capital works projects and private development investments are projected to increase spending by 2.8% annually within the industry through 2022 (Richards and Terkanian 2013; Henderson 2013). Subsequently, the Bureau of Labor Statistics reports that employment within the industry will grow upward of 11% by 2026 to meet this demand (Henderson 2013; Toossi 2013). Despite this steady increase in economic activity, the industry is anticipated to struggle to supply and adequately train new professionals entering into the building labor market (Toossi 2013; Henderson 2013; Li et al. 2011; Teicholz et al. 2001).

Over the last two decades, industry practitioners have reported alarmingly low numbers of new professionals entering the building industry. The problem is compounded as the median age of construction professionals has risen to 42.7 years of age and 44 years of age for design-related fields, causing the industry to face what has been coined a *labor cliff* (Goodrum et al. 2016), defined as a labor state in which project performance is significantly affected by one or more workforce issues including labor supply (Teicholz et al. 2001; Taylor et al. 2016). Although originally defined for craft labor, management positions in construction- and design-related fields mirror the trends seen through craft labor in the industry. The median age of workers in management positions in construction has grown to 47.8 years of age and has risen to 49.5 years of age for designing- and engineering-related fields (Bureau of Labor Statistics 2017). This means that current industry experts are approaching the age of retirement and the expertise that they have developed throughout their career will also exit the industry. Consequently, a need is presented to find an effective means to streamline the development of this expertise for the next generation of construction industry professionals.

Industry Education Knowledge Formation

Traditionally in design and construction education, the dissemination of information to students uses manuals or standard operating procedures, which target explicit knowledge (Hizar Md Khuzaimah and Hassan 2012). While explicit knowledge is undoubtedly important for the next generation of industry practitioners to have, tacit knowledge, which is typically developed over years of experience (D'Eredita and Barreto 2006), may be especially critical as current industry members with years of experience, and tacit knowledge, retire. The recognition of the importance of tacit knowledge is also echoed by industry practitioners, who often place a higher value on the knowledge gained through experience (Hizar Md Khuzaimah and Hassan 2012). Given the industry's pressing need for new professionals with tacit knowledge, there is a need for educational researchers to identify methods to reduce the time required for preparing individuals for their careers with this critical knowledge.

A multiyear study conducted by the Sullivan and Rosin (2008) across multiple institutions analyzed the current state of undergraduate engineering education in the United States. The study was intended to provide institutions and educators with recommendations for improving the current curriculum taught to students in order to better prepare them for their careers within their associated fields. At the conclusion of the study, researchers explained that educational programs within engineering-related fields do well at targeting explicit knowledge or technical knowledge within the current curricula (Sullivan and Rosin 2008). However, researchers go on to describe a need to have more integrated learning experiences to develop tacit knowledge that incorporates lessons involving knowledge (head), skills (hand), and professional judgment (heart) (Sullivan and Rosin 2008). The three apprenticeships model is derived from these findings, where each of the identified elements is defined as an apprenticeship of learning (Sullivan and Rosin 2008).

For construction-related professions, the *knowledge* or *head* apprenticeship would include the industry-specific information an individual must retain to operate within the field, typically shown in manuals or textbooks. The *skills* or *hand* apprenticeship includes the practical ability for an individual to complete a task. Lastly, the *professional judgment* or *heart* apprenticeship relates to the ethical or moral decisions that must be made by designers and constructors to complete a project. The study found that the professional judgment (heart) apprenticeship was most underrepresented within engineering education-related contexts (Sullivan and Rosin 2008). The model suggests that curricula that integrate each of the

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apprenticeships identified would theoretically allow for more well-rounded development of students who could employ both explicit and tacit knowledge relating to their fields of study. This approach has been tested in the nursing profession resulting in improved preparedness of new nursing professionals (Taylor and Care 1999). While this approach suggests potential benefits for creating experiential learning environments that are conducive to tacit knowledge generation, this model has not been explored in the building design and construction education domains.

Virtual Environments and Opportunity for Building Education

Over the last few decades, visualization technologies such as VR and AR have begun to enter educational and training programs across multiple disciplines, such as the medical fields and law enforcement (Jetter et al. 2018). These technologies have been suggested to benefit education by allowing educators the unique ability to create immersive, three-dimensional, environments for students to explore in order to support learning (Russell et al. 2014; Wang et al. 2018a). Recent research has suggested that AR and VR may provide particular benefits to design and construction education (Wang et al. 2018a).

The two technologies offer a unique set of characteristics and interactions with virtual content, which researchers and educators may use to create different learning experiences that leverage differing types of immersion affordances with the virtual environment. VR is the presentation of a fully synthetic immersive visualization experience to a user (Marini et al. 2012; Woksepp and Olofsson 2008). When evaluating a user's sense of immersion and sense of place, VR was shown to be an effective means of recreating an experience that made users feel "as if they were there" (Matsangidou et al. 2017; Willis et al. 2017). VR has been suggested to trigger emotional and cognitive responses, similar to that of the real world (Matsangidou et al. 2017; Otto et al. 2005; Rekapalli and Martinez 2011; Willis et al. 2017). Unlike VR, which replaces the physical world, AR can be defined as the presentation of virtual content simultaneously with the real world around the user (Jetter et al. 2018; Milgram and Kishino 1994). AR allows unique physical affordances to the user, as he or she is not disengaged from the real world like in VR. Because of the differences in how AR and VR provide environmental context to a user, each technology may offer unique benefits (or potential drawbacks) for developing tacit knowledge by students.

Both AR and VR have been suggested to offer particular value for supporting design- and construction-related education (Wang et al. 2018a; Wu et al. 2013). Over the last few decades within AEC education and research, VR has been presented and tested with students in various learning use cases and applications with reported success (Li et al. 2018; Wang et al. 2018a). VR has been used for training new mining professionals about safety procedures and identified high usability ratings among users (Akyeampong and Udoka 2012). Sacks et al. (2013) also explored VR-based safety training and observed benefits over traditional classroom training, noting that VR could be used to manage trainees' attention for extended periods of time and maintain better participant alertness. Pedro et al. (2016) echoed this finding by demonstrating that VR improves students' ability to recognize hazards and transferring safety knowledge while maintaining student engagement. VR has also been found to promote understanding of the spatial and temporal implications of a design by allowing students to visualize general space constraints or scheduling conflicts more quickly and easily (González 2018; Nikolic et al. 2011). These studies highlight the benefits that can be provided by exposing students to virtual experiences that would otherwise be too dangerous or costly to physically model for students.

More recently, AR has also been suggested to provide benefit to the training of novice construction and design professionals across an array of applied use cases. Ng et al. (2011) studied the use of AR for model visualization and model modification through a gesture-based AR design evaluation (GARDE) system and found that users were able to contextualize designs and utilize spatial information from the environment to make more-informed design modifications while providing a highly interactive experience. Similar to VR, AR has also been helpful in assisting educators in facilitating a better understanding of spatial–temporal constraints of a space when compared to traditional classroom lecture procedures (Gonzalez 2018; Shanbari et al. 2016). In a study conducted by Chalhoub and Ayer (2017), AR was shown to offer benefits for construction professionals' comprehension of design information in order to complete a simple construction task in an accurate and efficient manner. Recently, with the introduction of eye-tracking capabilities into wearable AR devices, researchers were able to explore the efficiency of AR from a cognitive perspective by tracking visual behaviors of users and found that AR-based environments promoted higher learning performance due to increased generative processing by students (Wang et al. 2018b). These prior studies illustrate the potential of AR for educational and training applications, but the ways in which this mode of visualization enables tacit knowledge generation remain unclear.

The prior works illustrate various affordances of both AR and VR that are provided by the unique immersive experiences that these visualization technologies enable. These attributes may provide virtual experiences that mimic the types of actual experiences that students would encounter in their careers. Therefore, the authors of this paper specifically explore how these technologies may support, or potentially hinder, behaviors that indicate tacit knowledge among students pursuing building-related educational disciplines. Furthermore, by specifically targeting the professional judgment (heart) apprenticeship, researchers will record and identify specific behaviors elicited in both environments and the unique aspects of each that may lead to or hinder more-informed and empathetic design assessments among students.

Methodology

The methodology of this work involved three core steps: identification of targeted apprenticeship and associated design assessment task considerations; development of pre- and postactivity assessments to measure shifts in perceptions of participants; and video recording and analysis to study observed behaviors of participants in the design assessment activity. This methodology provides data that enabled the researchers to understand the perceptions and behaviors that were elicited through VR and AR environments. The following sections detail the methodological tasks involved in each of these three steps.

Step 1: Expert Interviews and Establishing the Design Assessment Task

Expert Interviews

In order to develop a design assessment task that is both relevant to the building industry and requires the targeted heart dimension of the three apprenticeships model (Sullivan and Rosin 2008), the authors conducted expert interviews with current industry practitioners, each with over 10 years of experience. More specifically, the interviewees all had prior experience in designing for individuals with needs different from their own. For example, they possessed experience designing for handicap accessibility, detention facilities, and facilities for individuals with severe mental health issues. This prior experience and background provided the interviewees with relevant expertise that could support their responses to interview questions.

The interview protocol developed for this activity consisted of open-ended questions that were based on the working knowledge and working experience of the industry experts. The questions were framed in a manner to have participants reflect on previous career experiences that required them to consider the needs of someone else. Specifically, the developed questions guided participants to discuss times in their careers when they were required to exercise professional judgment based on morality and ethics. For example, questions asked included: what is your approach for designing something that is inclusive to a diverse group of individuals?; how do you handle issues of diversity (e.g., ability/disability) in the design process?; and what is your approach to evaluating different design decisions? The questions were intended to elucidate the decision-making processes used by experts to address the design challenges that they mentioned.

The findings from the interviews guided the authors in their development of a design assessment activity to focus on handicap accessibility to be performed by novice building professionals. When designing buildings for someone in a wheelchair, the interviewees frequently talked about potential challenges related to designing a space that the targeted building occupant would be able to effectively use during operation. During the discussions, participants mentioned that sometimes designers, often earlier in their careers, follow code requirements, but do not fully consider how someone in a wheelchair would actually navigate the space.

For the purposes of this study, *novices* were assumed to be individuals who were pursuing upper- and graduate-division coursework in a building-related field, including construction management, construction engineering, and civil engineering. These individuals were targeted for study because they would likely be involved in design and constructability review sessions in their future careers, but as students, have limited working experience within the building industry, which likely limits their level of tacit knowledge. The assessment task developed required novice building professionals to identify aspects of a building design that would not effectively support an occupant in a wheelchair and suggest possible options to improve accessibility.

Development of Design Assessment Task in the Virtual Environments

In order to incorporate aspects of the design that could potentially include the same considerations mentioned by the expert interviewees, very small approximately 15 m^2) residences were chosen for evaluation. Two different design models were chosen. Each model was roughly the same size and included four basic spaces: sleeping area, living area, kitchen, and bathroom. Images of both models are shown in Fig. 1. Both models were originally developed by student designers and were not created with handicap accessibility in mind. As a result, both models had a multitude of potential problematic design elements related to handicap accessibility.

Both models were developed in both AR and VR environments using Unity game engine. AR content was developed using Microsoft Hololens. VR content was created using HTC Vive. The models were unmodified from what students developed except for small modifications to support clear rendering of the spaces (i.e., deleting redundant geometry or removing erroneous geometry that was outside of the design assessment spaces). The modeled content was scaled to 1:1 in VR and AR versions to allow a user to perceive each at their full scale.

While the modeled content built to each mode of visualization was identical, the navigation process required for each format differed slightly. By the nature of AR, users view virtual content on top of a physical space, while VR completely replaces the physical environment with virtual content. As a result, the VR experience included a point-and-click navigation approach that used the default HTC Vive wands. Users could view a completely virtual version of one of the buildings and would also see a virtual laser pointer in the VR environment. They could select a point on the ground and instantly move to that location. Furthermore, if participants wanted to look around the space, they could simply turn their heads to see different directions in the VR environment. For the AR environment, users would view virtual content on top of their physical space. In other words, users would see the virtual version of the building, but when they looked downward, they would see their actual body, not a virtual representation of a body. This type of interface removed the need for virtual navigation to be programmed into the experience. Instead, users were placed in a physical wheelchair and instructed to physically navigate the space as they conducted their design assessment. This meant that they could observe their physical body and wheelchair as they navigated through an otherwise virtual environment. In both instances, users viewed full-scale modeled content from a seated position, but with different navigation approaches based on the affordances of AR and VR. This development strategy allowed the authors to specifically study how these different environments would impact students' design assessment process.

Participants' Experience in the Virtual Environments

Participants were randomly assigned an initial house model (i.e., 1 or 2) and visualization format (i.e., AR or VR) for completing their initial handicap accessibility design review. For the second review activity, they were provided with the other model and other visualization format. The counterbalanced random assignment of model

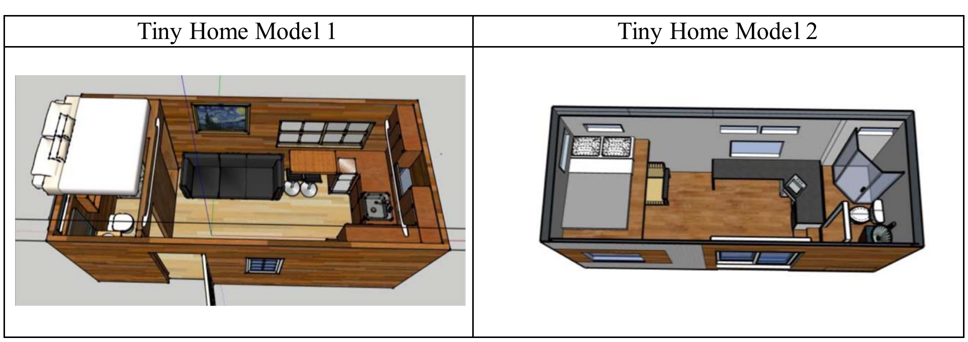

Fig. 1. Tiny homes used in design assessment activity.

and visualization format to the different participants helped to offset potential patterns of behavior related to model-specific attributes or review experience gained in the first review activity with a particular visualization mode, which might theoretically influence their behavior (Pollatsek and Well 1995).

When participants began the review activities, they were introduced to the navigation approach required for their assigned virtual environment. When they were comfortable with navigating the virtual spaces, they were asked to verbally state their concerns through a think-aloud protocol. Think-aloud protocols can help to understand the problem-solving strategies used by participants during an activity and also their high-level thought process involving working memory (Joe et al. 2015; Olson 1983). For this work, the think-aloud protocol involved participants talking through concerns that they had for the different virtual models. In some instances, participants would state initial concerns, but then clarify that the building element was acceptable after exploring the space. In other instances, the concerns they voiced indicated problems that would need to be redesigned for wheelchair accessibility. Many times, participants suggested potential design solutions when they stated their concerns. If participants did not suggest a design solution, a researcher asked them if they could provide a suggestion to improve accessibility. All participants were audio and video recorded so that researchers could study their behaviors and statements in subsequent analysis.

Step 2: Development of Pre- and Postassessment Questionnaires

In addition to exploring the observed behaviors and statements made by participants, the researchers also aimed at understanding the perceived impact of the two environments and, by extension, the technologies used. Therefore, the authors of this paper developed a set of pre-/postquestionnaires to collect various data from each participant before and after the design assessment activity. This approach enables for statistical analyses that are more powerful and allow for smaller sample sizes (Brogan and Kutner 2012). The survey data were used to determine whether significant changes occurred in the users' perceptions of AR or VR after the design assessment.

When participants began the research, they were presented with an online questionnaire that included an informed consent screen, in accordance with the researchers' Institutional Review Board. After agreeing to participate in the study, participants completed the preactivity questionnaire. This questionnaire included questions to elicit responses related to participants' prior working knowledge and experience within the building industry and also their educational background. Additionally, participants were asked about their perceptions toward the technology and their own ability to complete the design review task well using a series of 5-point Likert-type scales. For example, "On a scale from 1 to 5, 1 being least agree and 5 being most agree, please indicate your level of agreement with the following statement: I felt AR provided me enough information to effectively assess design elements."

After completing the preactivity questionnaire and design review activities, participants completed a postactivity questionnaire. This postactivity questionnaire intentionally targeted similar information to the preactivity questionnaire in order to measure shifts in perception among participants. Additionally, open-ended questions were developed to allow for greater reflection by each participant, which may illustrate thought patterns that were not specifically reflected in the responses to prior questions. For example, "What did you like best about the activity?" and conversely "What did you like least about the activity?"

Step 3: Development of Criteria and Scheme for Behavioral Analysis

Each participant was video recorded during the design assessment activity in order to record the verbalized design assessment comments made during the activity and also to evaluate the physical interactions that were observed. These videos enabled the researchers to define specific behavioral codes to identify common trends among participants. This behavioral coding approach to video analysis has been used by several prior studies in AEC contexts that aimed at conducting statistical analyses related to the observations of participants (Alsafouri et al. 2017; Liston et al. 2001).

In order to record the commonly identified design elements that were suggested to be problematic by participants, the responses captured through the video recordings were identified and then categorized based on the building element for which the comment was related. For example, if a participant stated "the countertop seems it may make things out of reach and not useful," this statement would be categorized as *countertop height accessibility* in the video coding scheme developed. Using building elements that were consistent between the models to organize the spoken comments helped to provide a consistent context for organizing the otherwise unstructured data provided by participants.

In addition to exploring the spoken statements of participants, the researchers also aimed at studying the physical behaviors demonstrated by the participants. Similar to the approach used for defining spoken behavioral codes based on trends observed in the data, the researchers also studied the physical movements and behavioral trends observed among participants. Based on these observations, a detailed coding scheme was developed to characterize and quantify the frequency of these physical actions in the AR and VR environments. Three critical behaviors were observed among participants during the activity, which are shown in Table 1.

Table 1. Physical interactions tracked

Interaction	Example behavior	Rationale
Arm interaction	Participant reaching into space to mimic touching or using spaces within the model as if the participant was end-user	Tracks instances participant is engaging in physical exploration with the use of the mimicked tactile interactions prior to giving comment
Quantifying visuals	Participant using hands (AR) or controllers (VR) or additional visual cues such as the body to evaluate a distance	Tracks instances of physical engagement of participant when estimating measurements by spanning the arms in a manner similar to the use of a tape measure or comparing model objects against additional visual cues prior to giving a comment
Prop interaction	Participant using wheelchair (AR) or either rotating in the office chair or grabbing its sides like wheels on a wheelchair (VR) to check the spacing of model elements	Tracks instances of participants utilizing the wheelchair or rotating in a chair to mimic the use of the space, similar to the end-user, prior to giving a comment

Results and Discussion

The data collection for this paper was conducted in the spring of 2018 in two locations: a regional conference for architectural, engineering, and construction (AEC) students and experts and a large Southwestern university. Nineteen students participated in this research and completed all questionnaires. This group of students was recruited through email announcements and by a physical poster announcing the research activity at the conference. The participants included 13 undergraduate seniors, 5 undergraduate juniors, and 1 graduate student. The sample population had generally low levels of industry experience, with all 19 having fewer than 4 years of industry working experience. All participants were from building-related disciplines, including construction management and construction engineering programs. Twelve students who participated had previous personal experiences with family members or friends who required the use of a wheelchair, but none of the participants reported ever having a personal need for a wheelchair. Eleven participants had never used VR before, and 15 students had never used AR previously. This sample of students was chosen to represent individuals who could be considered a novice population because of their low levels of practical work experience, minimal AR and VR experience, and limited background knowledge on handicap accessibility. The following sections present the findings related to these students' behaviors demonstrated, comments made, and perceptions reported.

Findings Related to Behaviors Demonstrated and Statements Made Between AR and VR

Identified Accessibility Concerns

All 19 students were able to navigate and identify design concerns related to handicap accessibility within each model and both visualization formats. Overall, students interacted with the modeled content in AR 3.47 times on average throughout their design assessments, while students using VR interacted with the model 2.26 times on average. This difference is significant at the 95% confidence level with a p-value of <0.001. This suggests that, while both immersive environments can encourage users to physically interact with virtual components, AR seems to encourage these types of behaviors more than VR. This finding is largely intuitive, as AR does not replace a user's view of him or herself while in the experience. Therefore, while AR and VR can both support physical interaction with virtual components, AR supports interaction in a way that is innately familiar to participants.

In addition to exploring the overall physical interaction behaviors demonstrated by participants, the overall number of design assessment statements was also analyzed. The total number of reported concerns was similar in both visualization environments, as shown in Fig. 2. Participants within AR reported an average of 8.4 accessibility problems per design review that they believed would require modification for a wheelchair-bound occupant. Participants in VR identified an average of 8.9 concerns per model. The authors were interested if there were any statistical differences between the comments made and conducted a paired sample t-test in order to compare the two environments. While numerically different, these averages did not indicate statistically significant differences at the 95% confidence level. Furthermore, both formats led participants to generate accessibility-related comments in all areas of the house models that were provided. This seems to suggest that both formats enable similar numbers of design assessment comments by students to be generated for accessibility throughout all modeled spaces.

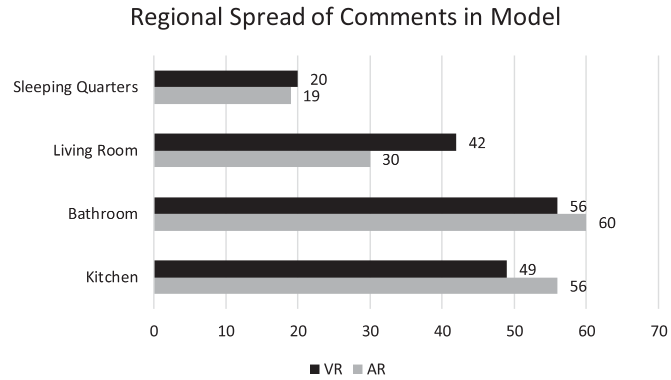

Fig. 2. Regional comment spread.

Impact of Differences in Physical Navigation Abilities and Resultant Design Assessments

While the number of comments made by participants in the different visualization environments did not indicate substantial differences between AR and VR overall, the specific types of comments did indicate some noteworthy trends. In VR, participants reported *door access* being an issue to handicapped users a total of 12 times. Typically, this comment related to a doorway that they believed was too narrow to navigate with a wheelchair. Conversely, in AR, participants only reported the same door access concern four times in total. On the surface, this data might seem to suggest that VR leads to a higher recognition of design limitations related to access. However, when the specific door widths in the model were actually measured from the models, all doorways were 32 in. wide (0.813 m), which does adhere to acceptable residential door width guidelines according to the Americans with Disabilities Act (ADA) requirements (DOJ 2010). Furthermore, the researchers observed evidence that suggests that the participants in AR likely considered door widths during their design assessment. For example, every single participant in AR physically navigated through the doorway using the wheelchair provided. While the researchers cannot make claims about exactly what participants were thinking during this navigation, several participants voiced initial comments about the doorway width seemingly posing a concern, but then, after navigating through it in the wheelchair, withdrew their concern when they saw that there was adequate space. For example, one participant stated "If I were in a wheelchair living here I would probably adjust this later, but the door works for now." The finding that VR may have led to inaccurate perceptions of spacing aligns with the findings of prior research that demonstrated potential dimensional inconsistencies among participants in VR (Saleeb 2015). The more noteworthy finding is that this tendency seems to be partially mitigated through AR by adding a real object that is accurately scaled (i.e., the real wheelchair that participants used). This seems to suggest that the physical navigation affordances of AR were not mere novelties, but that they actually impacted how students considered design decisions for access in the space related to this navigation.

Furthermore, the difference in navigational behaviors between AR and VR may suggest different applications of tacit and explicit knowledge among participants. For example, while students in construction-related disciplines may not know exact ADA requirements, they are likely aware that codes exist related to this. They are also likely to be aware of the fact that door width spacing would be a consideration within ADA, even if they do not know the exact requirement of what this spacing must be. This type of knowledge can be considered *explicit* because it is easy to access, articulate, code, and verbalize (Collins 2010). Conversely, tacit

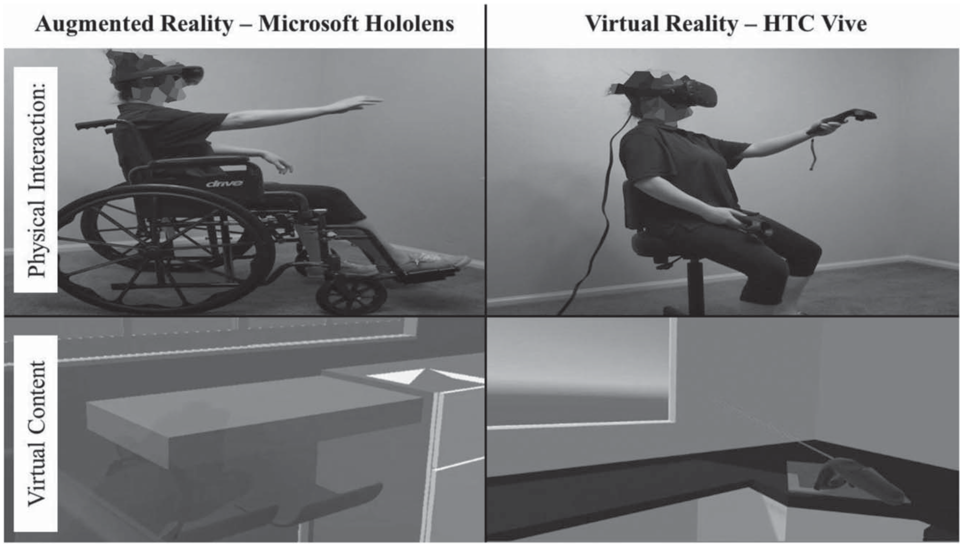

Fig. 3. Example arm interaction in both environments. (Images by authors.)

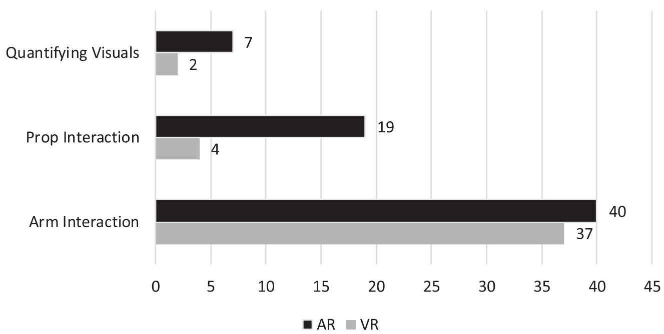

Fig. 4. Physical interaction comparison.

knowledge is associated with knowledge related to completing tasks and may be more challenging to articulate (D'Eredita and Barreto 2006). This aspect of *completing tasks* that relate to physical navigation seems to differ between AR and VR. In AR, participants can physically *complete the task* of navigating through a doorway in the wheelchair, while in VR, they may only virtually complete the task. The combination of findings that all students in AR navigated through the ADA-compliant doorway, with several even making statements indicating their consideration of its width, but only a few reporting it as a problem, may indicate that students exercised a form of tacit knowledge in a way that was not observed through VR because of their ability to physically complete the task of navigation.

Impacts of Analogous Physical Interactions between AR and VR and Resultant Design Assessments

The physical navigation differences between AR and VR seemed to suggest potential differences in how they guided students' exploration and subsequent design reviews. To better understand the extent to which this type of physical exploration influenced students' comments, the authors also explored physical interactions that were largely similar between the two formats. In both AR and VR, participants could use their hands to reach out and interact with virtual objects. In AR, they would see their real hands interacting with virtual objects. In VR, they would see imagery of the controller wands tracked in real time. While these wands were initially provided to participants for navigation, all participants used them at some point in the activity to reach out to interact with virtual geometry. Participants in both interfaces used their hands a comparable number of times. Examples of this interaction in both environments can be seen in Fig. 3. Similarly, it was interesting to note that they reported similar types of concerns after making arm interaction gestures. Furthermore, they reported these concerns at similar rates between AR and VR.

For example, in both AR and VR, participants frequently reached out to touch the model. While they were in the kitchen region of the model, they often reached to the countertop in order to see if they could complete a simple cooking-related task. In most cases, participants immediately followed this interaction with a comment suggesting the countertop was too high for easy access in a wheelchair. This provides further evidence that, when participants are provided with the opportunity to physically interact with virtual components in order to complete a task, it not only provides a novelty, but also impacts the types of design assessments that they report.

While the participants had comparatively similar abilities to use their hands in both environments in order to interact with the virtual components, as shown in Fig. 3, the ways in which they interacted with AR and VR environments for the other behaviors tracked differed more drastically, as shown in Fig. 4. Quantifying visuals indicates a behavior where users span their hands to help determine adequacy of spacing in the model. While participants could do this in both environments, it was observed more with AR. This may be partly explained by prior research that indicates that VR can be prone to communicating dimensions with varying levels of perceived accuracy (Saleeb 2015). Similarly, prop interaction involves turning in the provided wheelchair in AR or turning in the provided office chair in VR. While both groups had the ability to turn in this manner, participants in the AR group did this far more. When engaging in this behavior, participants appeared to see if there were sufficient turning radii in the spaces to allow a wheelchair-bound occupant to turn. While AR led to more of this type of behavior, it is worth noting that the VR model used did not include a representation of a user's body with an avatar to provide a visual cue to assess adequacy of spacing for turning. It is possible that if this had been added, participants in VR would have performed this behavior more frequently in order to determine if their virtual body clashed with the virtual space (Fig. 4).

Assessment of Intermodel Validity and Order of AR/VR Usage

The behaviors and design assessment statements provided by participants provided some noteworthy trends, but they also included students completing multiple design assessment activities using two different tiny house models. While some aspects of the model were objectively similar (i.e., both models were of similar sizes and had the same functional spaces), it is possible that there could be specific nuances between the models that could make one more challenging for users completing the assessment tasks. The authors used a counterbalanced approach to randomly determine which model and which visualization format participants would use first to help mitigate potential effects of learning from the first design assessment. To further verify the lack of impact of difference models or order of AR/VR usage, the authors analyzed the observed data to identify if any trends indicated differences in performance.

For assessing differences related to the two tiny house models, the authors did not observe any data that overtly suggested differences in difficulty. For example, since students had the freedom to declare when they were finished with the design assessment, a more difficult model could have required more of their time for them to feel comfortable with their assessment. Therefore, total times explored in both models were identified. Both models resulted in similar overall times of exploration, with one observing 296 s of participant exploration and the other resulting in 289 s of exploration. It is worth noting that participants generally spent less time assessing whatever model was randomly selected to be their second model. The average difference in time between their first and second assessments was 19 s, but this difference was not significant at the 95% confidence level. Although the average difference between times of exploration is not statistically significant, it is possible that participants' improved ability to identify design considerations in the second review because of the preceding first review experience enabled them to finish faster. It is also possible that participants perceived this second activity as repetitive and may have elected to declare that they were done sooner. This difference in order was observed regardless of which model participants used first. Therefore, this does not indicate that either model was more challenging for design assessment, based on the time it required for assessment by participants.

The authors further analyzed the findings to determine if there was evidence that participants made different numbers of comments between their first and second review. It is possible that if differences were significant it would indicate that students did not put the same level of thought into the second design assessment. On average, participants voiced 8.3 comments in the first design assessment activity, regardless of which model or visualization format they used first, and they voiced 8.6 comments for the second assessment activity. This suggests no significant difference.

In addition to exploring potential differences between models, the authors also aimed at identifying any potential differences that could have influenced participant behavior based on the order in which they used AR or VR. The average time spent in AR by participants who used it for their first assessment was 308 s, while the average time spent using AR for the second review was 285 s. The average time spent in VR by participants who used it for their first assessment was 321 s, and the average time spent using VR for the second review was 292 s. These results indicate statistically significant differences ($p < 0.001$) between the first and second assessments, but they do not indicate statistically significant differences between AR and VR. Furthermore, when average times between all participants were analyzed, AR was used for 291 s per design assessment, and VR was used for 294 s. This also does not represent a statistically significant difference.

The combination of these findings indicates that, while there is evidence of a difference in participant behaviors between design assessment activities, there is no evidence to suggest that this difference was the result of differences in the models used or the order of AR/VR usage.

The behaviors observed indicate that AR/VR may offer opportunities for enabling students in construction-related disciplines to use or develop tacit knowledge in ways that had not traditionally been possible without field experience. While the exact ways in which these visualization media may be implemented in construction curricula may vary by institution and educator, the results observed may help to inform how educators use these tools. For example, the results observed suggest opportunities to incorporate AR and VR for courses where students are introduced to building codes, such as ADA, that may impact design and constructability. The findings in this work suggest that students may be able to effectively recognize the need for these types of codes for a particular space using AR and potentially VR. It is likely that the type of learning experience provided by physical exploration of a virtual space will enable other forms of education as well, such as sequencing for specific construction tasks that may be new to students. However, because of the specific nature of this initial study, the authors do not make definitive claims about the extent to which AR and VR will impact other types of education that were not explored in this work. Similarly, because this work focused on students in construction-related majors, the authors do not make claims about what behaviors might be demonstrated by students in other domains, such as architecture or civil engineering. As future educators and researchers from various building-related fields adopt this type of learning environment and publish results, the body of knowledge will continue to better define the contexts in which AR and VR do and do not support tacit knowledge among students.

Findings Related to Perceptions of Usability of Technologies Reported by Participants

All participants who performed the design assessment in both environments also completed pre- and postactivity questionnaires that elicited responses related to their perceptions of the experiences. All participants reported that the two devices gave them enough information to perform the design assessment task during the activity. In relation to the entire activity, participants reported a relatively high level of perceived ability to both assess design elements and assess construction decisions, with average Likert scores of 4.3 and 4.4, respectively. This was of interest to explore in order to ensure that participants did not feel as though they were asked to complete a task for which they were entirely unprepared. If the scores had been far lower, it could suggest that the participants were effectively set up to fail in the design assessment task. Therefore, these perception results suggest that the participants felt that they were generally capable of completing the required tasks.

In addition to analyzing the students' perceived ability to complete the activity, the authors of the paper were interested in understanding the perceived usability of each visualization device when completing the design assessment activity. While the observational data indicated several trends in behaviors and statements that suggest value related to the physical affordances of AR, the survey responses indicate that this same recognition of value was not always reported by the participants. For example, the open-ended question survey data indicated that students generally felt that VR was more user friendly. However, when asked to provide Likert-scale responses, this preference for VR was less apparent. For example, the reported ease of use between the two devices was approximately the same with average Likert scores of 3.9 for AR and

4.1 for VR. This is further supported by the perceived level of confidence and level of cumbersomeness when using each device. With both devices, participants reported an average Likert score of 4 for their perceived level of confidence. In addition to the similar levels of confidence, participants reported similar levels of perceived cumbersomeness of the devices with average Likert scores of 2.2 with HTC Vive and 2.4 with Microsoft Hololens. The only noteworthy usability differences identified related to the complexity and inconsistency of each device. Participants indicated that the AR experience was slightly more inconsistent and complex when compared to the purely VR experience. While this seems to suggest a slight preference to VR related to certain usability considerations, there was no evidence in the observational data collected to indicate that these preferences hindered the participants' ability to complete the design assessment activity.

This comparatively negative feedback toward AR may be explained through the responses to the open-ended questions regarding the experience in the postquestionnaire. Nearly all negative comments regarding the usability of Microsoft Hololens were reflective of the limited field of view provided by the device. However, participants did reflect positively regarding the navigation and interaction allowed by the AR experience. Although challenges were indicated within the questionnaires by participants, all participants suggested potential for the use of each technology for education and practical applications. Given the specifically mentioned narrow field of view that was present on the AR device, this may suggest a direct opportunity for trying similar design review activates with next-generation AR head-mounted displays that are lighter and have a larger field of view to see if perceptions improve.

It is also worth noting that students reported these perceptions before completing either design review activity and also after they completed both reviews. In other words, they did not directly provide perception-based data on a questionnaire in between the two design assessment activities. It is possible that if this had been done, students would not have reported concerns with the field of view or weight because they would not have had the opportunity to compare one device to the other. Conversely, it is also possible that they would have rated both devices lower as both require them to wear a display on their head, which may feel heavy for participants who have not had substantial experience with AR or VR.

Due to the specific nature of the questions of interest for this work and the use-case explored for the study, there was not a previously validated questionnaire that the researchers could directly use. As a result, they developed survey questions to be addressed by participants who would directly relate to the experiences tested. While the authors used accepted structures for defining questions (i.e., Likert-style scales) and attempted to create questions that were difficult to misinterpret, it is possible that the exact phrasing of questions could have introduced some unintended biases in responses. Therefore, the authors recognize that the exact magnitudes to which participants responded to certain pre- and postactivity questions may not be exactly replicated by future research.

Conclusion

This paper explores the use of AR and VR to support the exploration of virtual spaces in a manner that aims to authentically replicate the type of physical interactions that would be expected in the building industry. While there are certain practical limitations of how authentic a virtual experience can be, this work found several noteworthy patterns of behavior and design assessment statements that suggest that both environments can offer some support for this type of learning experience.

The purely synthetic VR experience enabled students to express design concerns related to topics that indicate the use of explicit knowledge. However, when students were able to physically interact with the virtual spaces in both AR and VR, they were able to not only express explicit knowledge, but also demonstrate behaviors that suggest tacit knowledge as they completed tasks in a manner similar to what an eventual building occupant might do. For example, in AR, participants could physically reach their arm to touch virtual objects and judge the effectiveness of the design based on their own ability to reach. In VR, participants could see the tracked controllers in their view in order to assess the extent to which the design supported their needs. These behaviors led to comments that implied the use of tacit knowledge in a way that was not observed when students could only look at a synthetic VR environment.

In addition to conclusions related to the use of tacit knowledge when participants were enabled to physically engage with the model, the results from this work also indicated that this mode of interaction supported design considerations for occupants who may have needs that are different from the student participants. This was evident through the handicap accessibility-based activity that tasked participants, who had never required the use of a wheelchair, to navigate in a wheelchair to create their design assessments. As compared to VR, which only simulated navigation in a wheelchair, the behaviors and statements made in AR seem to suggest a more overt consideration of the needs of eventual wheelchair-bound occupants. This suggests that this mode of interaction may provide an opportunity for educators to more directly target design assessment learning activities that target heart-related apprenticeships, which have not traditionally been stressed in engineering-related educational settings.

The combination of these conclusions indicates that the physical exploration affordances of both AR and VR not only provide a novel design assessment experience, but actually impact the types of decisions that are made by student participants. The authors do not claim that AR is better than VR, because in the instances where participants had the opportunity to physically explore VR, they generated similar responses to AR. Therefore, it is more accurate to conclude that the physical exploration of a space in a manner that sufficiently replicates the experience of the targeted end-user can support students in demonstrating the type of tacit knowledge that was observed in this work. While this type of interaction can potentially be simulated in VR or AR, AR does offer certain practical advantages because it allows educators to simply use real objects, where possible, which eliminates the need to consider how effectively VR content can sufficiently replicate the experience that would be expected of real end-users.

Interestingly, the students' perceptions reported in the pre–post-questionnaire did not always echo the findings that physical navigation supported their design assessment. Many students stated that they preferred the use of the VR environment because of the comparatively lightweight head-mounted display (HMD) and also because of the wider field of view. This perception data suggests an opportunity for future researchers and developers to explore newer AR devices with lighter weights and wider fields of view. Despite the perceived technological limitations of the current-generation AR device used, the observational data indicate that the physical affordances offered through AR can still support students in demonstrating tacit knowledge generation for handicap accessibility design assessment tasks. This provides evidence that may guide future educators to elect to use AR for helping students gain exposure to situations where they may be able to develop tacit knowledge for building-related fields.

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