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Development of Virtual Tours for Understanding the Built Environment of an Educational Building

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Abstract: Though we spend a significant amount of time in indoor and built environments as general occupants of residential or commercial spaces, we do not necessarily know how the heating, cooling, and ventilation services work in our occupied spaces. As the mechanical systems of buildings become more complex for energy saving and better indoor air quality, it is beneficial for occupants to learn more their built environment so that they can cooperate effectively for the building's performance. In this context, the purpose of this research is to develop and evaluate how virtual reality (VR) technology can support occupants in understanding their built environment. An educational building on campus was selected for the development as it provides familiar spaces for potential participants in this research. This research was carried out in two stages. In Stage One, we, as researchers in mechanical engineering, explored the workflow for VR development and developed VR tours for four spaces: a classroom, an auditorium, a conference room, and a mechanical room. In Stage Two, we conducted a survey study to examine the VR experience from the perspective of users. In this survey study, we recruited 34 participants from engineering students/graduates, industry participants, and a sustainability group. The participants generally indicated a positive experience with the VR tours, although the quiz scores on the VR content were weak. From our reflection, we consider that positive and effective VR experiences for the education of the built environment require collaboration from three domains: (1) mechanical systems of buildings, (2) VR technology, and (3) pedagogy.

Keywords: virtual building tours; survey study; HVAC education

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1. Introduction

While people in developed countries can spend more than 90% of their time in the indoor (or built) environment [1], we (as general occupants) do not necessarily know how our occupied spaces are heated, cooled, and ventilated. If occupants can better understand their built environment, they can act as cooperative agents to improve their satisfaction and the space's indoor environmental quality (IEQ). For example, closing window blinds (as a cooperative action) can be more effective than reducing the thermostat's setpoint to manage thermal comfort in the summer. As another example, Abouleish [2] stated that human perception of the risk of COVID-19 can affect how occupants behave. For instance, some occupants may perceive outdoor air as a source of COVID-19 and keep their windows closed, causing poor indoor air quality (IAQ). The experiments by [3] demonstrated that occupants could base their perception of IAQ on thermal comfort if they did not receive any IAQ measures. As one conclusion from their review, Frontczak and Wargocki [1] considered that the possibility for occupants to control their occupied spaces can promote their comfort and satisfaction. Understanding of the built environment at the occupant level should be considered as a criterion to empower occupants as cooperative agents in the indoor spaces.

Typically, components for heating, ventilation, and air conditioning (HVAC) systems are not apparent or hidden from occupants, and their functions are automated with a minimum level of control from occupants (e.g., thermostat setpoints). Thus, it is understandable that occupants do not pay much attention to how their occupied space is thermally conditioned and ventilated. Yet, occupants can still be curious about how HVAC systems work in their spaces. In this context, the purpose of this paper is to explore the use of augmented and virtual reality (AR/VR) technology as a learning tool for occupants to learn their built environment. This paper will report our development of the virtual tours for a university building and a survey study to examine this development.

The choice of AR/VR technology as a learning tool is rooted in the concept of telepresence, referred to as the "mediated perception of an environment," in contrast to physical presence as "natural perception" [4] (p. 76). As occupants in their physical presence of the built environment typically employ their "natural perception" (e.g., physiological feeling of thermal comfort), occupants can also be "mediated" through communication technology to "see" or perceive nonexistent or hidden information. In view of occupants, AR/VR technology can make HVAC content visible in the physical space, and this is how we intend the learning moment to occur. Additionally, AR/VR technology can generally promote engagement in the learning experience [5,6]. We anticipate that AR/VR technology can make HVAC content more accessible for learners (as general occupants) who may find themselves less competent in understanding technical information. For example, AR/VR technology can illustrate HVAC content as virtual annotations and animated thermal effects, where occupants can directly associate such content to their built environment to promote their understanding of HVAC content.

In the rest of this paper, Section 2 will review the literature concerning the definition of AR/VR technology and its applications to building-related cases. Section 3 will discuss our development of virtual building tours. Section 4 will present and discuss our survey study for the virtual tours. Section 5 will conclude this paper.

2. Literature Review

In the literature, a wide range of applications of augmented and virtual reality (AR/VR) technology can be found for educational purposes. Examples of reviews for engineering education include [5–7]. For the domain of the architecture, engineering, and construction (AEC) industry, relevant reviews can be found in [8,9]. In [8], a decision-making framework was proposed to guide educators in selecting among four types of AR/VR technology (i.e., non-immersive VR, immersive VR, AR, and mixed reality) based on six educational priorities or considerations (i.e., visualization, motivation, interactivity, accessibility, risks on students, and risks of tasks). Tan et al. [9] provided a meta-analysis of 17 studies to examine the effect of AR/VR applications in education. Their meta-analysis indicated that AR/VR could provide a minor to moderate positive effect for education, and they stated that the limitations of AR/VR should not be overlooked.

As AR/VR technology advances with diverse possibilities, it becomes difficult to define and distinguish different terminologies (e.g., differences among virtual, augmented, and mixed reality). One classical classification is the reality–virtuality (RV) continuum [10], which covers the extent of virtual content on different displays. Notably, this continuum focuses on the functionality of display devices (i.e., how capable the displays are of rendering virtual content). In contrast, Steuer [4] suggested that virtual reality can be classified according to users' experience (but not based on physical devices). Skarbez et al. [11] argued that the RV continuum is discontinuous since the AR/VR technology does not address human "interoceptive senses" (e.g., users still know where they are physically even in an immersive virtual environment). Through focus group and expert interviews, Rauschnabel et al. [12] further suggested a sharp distinction (instead of a continuum) between AR and VR. To us, one convincing argument from them is that users can consciously tell whether their experience is associated with the physical environment (AR case) or with a completely virtual environment (VR case), but both types of experiences are not likely to exist at the same time.

Further, Rauschnabel et al. [12] proposed a continuum for each of AR and VR. For AR, a continuum is based on the "level of local presence" (from assisted to mixed reality), which concerns the "realness" of virtual objects perceived by users in the physical environment. For VR, a continuum is based on the "level of telepresence" (from atomistic to holistic VR), which can be interpreted as the immersivity of the VR environment perceived by users. Adopting the framework proposed by [12], this literature review classifies three building-related cases using AR/VR technology: (1) industry training, (2) cognitive learning, and (3) site visits.

The context of industry training focuses on the development of specific skills relevant to industry practices. In this context, safety training is particularly common because VR can allow trainees to learn from mistakes without the danger of real hazards. One primary function of VR is to render relevant visuals of construction sites for safety knowledge, hazard identification, and student assessment [13,14]. The study by [15] noted that VR intervention is more effective in safety training of specific works (i.e., stone cladding and cast-in-situ concrete) than general site safety. Joystick-type input devices have been applied with VR systems for the training of tower crane dismantlement [16] and excavator operations [17]. In addition, researchers have applied the stereo feature (i.e., background sound) and a shaker (to mimic the falling effect) to enhance the realism of VR experiences [18,19]. Since the abovementioned works tend to focus more on skill development than the "realness" of VR experiences, they can be classified to atomistic VR, which aims to deliver specific VR content rather than a high-quality holistic experience [12]. There are few examples of industry training using AR. In [20], AR is used to demonstrate how personal protective equipment (PPE) is worn virtually. In [21], Microsoft HoloLens was used to annotate information on wood framing for the construction task.

The context of cognitive learning focuses on the acquisition of content knowledge and the development of conceptual skills. When content knowledge and conceptual skills are taught in lectures, students can find it difficult to associate abstract content with situations in a real-life context. In response to this difficulty, AR/VR applications are intended to bridge this gap by placing virtual content visually in the associated environment. In the following paragraphs, we will discuss the applications of AR/VR with the classification of four educational purposes: (1) construction site knowledge, (2) building structures, (3) spatial reasoning, and (4) conceptual knowledge.

For the content knowledge of construction sites, one motivation of using AR/VR technology is to promote student motivation and visual learning. For example, Behzadan and Kamat [22] utilized interactive videos of a construction site and marker-based AR books to provide more visual experiences than traditional teaching. The study by [23] showed that the annotation feature on 360° photographs can enhance learning about a construction site. VR technology can also depict the construction process on a site over time [24,25]. Wang et al. [26] studied how task complexity on a virtual site might affect how students learn (i.e., learning styles), and they found that students did not significantly change their learning styles because of task complexity.

For the content knowledge of building structures, VR/AR technologies can support students in visualizing complex building structures. For example, Park et al. [27] combined a 3D building model with its anatomical structure (like a tree structure of components) in a virtual space. Lucas and Gajjar [28] used VR to support the teaching of a wood-framed structure and its assembly. In [29], AR was used to help students retrieve information about building materials in a model construction process.

Spatial reasoning requires students to evaluate 3D spaces using 2D or paper-based information, which remains the primary means of engineering communications. In this context, AR was used to render 3D information from 2D data [30]. Specific learning focuses can be found on the visualization of layout plans [31] and steel structures [32]. Hartless et al. [33] combined AR with physical wheelchairs to help students evaluate the accessibility of indoor spaces. Similarly to spatial reasoning, conceptual knowledge also requires some abstract skills. In this context, Turkan et al. [34] applied AR to help students visualize "unseen" forces on physical models. Huang et al. [35] applied AR to render finite element results on physical objects to support the understanding of structural analysis.

Kim et al. [36] applied computational fluid dynamics (CFDs) results in a virtual greenhouse to help students understand indoor airflow.

The last aspect of this review, site visits, concerns the applications of VR to promote the understanding of sites or buildings without specific focus on general skills and knowledge (e.g., construction safety or structural analysis). For example, Lassandro et al. [37] integrated energy analysis results and thermographic images in a virtual tour for people to understand the energy use of a historical building. Seifan et al. [38] developed a virtual tour of a wastewater treatment plant, noting that virtual tours can complement but not replace real tours. Due to the impact of COVID-19, Maltais and Gosselin [39] developed a virtual building tour, and their conclusion also indicated a preference for the complementary application of virtual and in-person tours for building education.

From this review, we should note that the applications of AR/VR for the AEC industry are quite abundant. As the learning curves and costs of AR/VR technology become more accessible, we expect the use of AR/VR to become more common for the public. While the reviewed works mainly focus on the formal education in specific courses, the focus of this paper is to develop and examine how the VR applications can promote the understanding of the built environment for general occupants.

3. Development of Virtual Building Tours

In planning virtual building tours, we have two types of target audiences in mind: engineering students and general occupants. For engineering students, the virtual tours are intended to help them understand how the major components of heating, ventilation, and air conditioning (HVAC) systems are installed in a building and learn their functions within the built environment. For general occupants, the virtual tours are intended to promote an understanding of their built environment with regard to heating, cooling, and ventilation functions.

To facilitate this development, we plan to choose one building on our university's campus, where we can access the building's information (e.g., building drawings, HVAC schematics). With more than 30 buildings on campus, we have chosen the Taylor Institute (TI) building (more details of the TI building can be found in this website: https://taylor-institute.ucalgary.ca/about/spaces-detail (accessed on 15 November 2023)) for two reasons. First, it is a relatively small two-story building (floor area about 3700 m^2 or 40,000 ft^2), allowing for the reasonable management of system complexity and development scope. Second, it features different types of spaces (e.g., classrooms, atrium, and conference room), enabling the virtual tours to illustrate how these spaces are conditioned differently. Notably, the building is in a cold climate region (e.g., 99% heating design temperature is −24.5 °C, dry bulb), where heating represents the primary energy need of the building.

The heating and cooling needs of the building are served by the district energy system, which provides hot and chilled water to most buildings on campus. Inside the TI building, the heating and cooling services are mainly delivered through the hydronic system (e.g., heating/cooling coils, in-slab heating/cooling, radiant panels). Two air handling units (AHU-1 and AHU-2) are implemented in the building. While AHU-2 is used to serve the heating, cooling, and ventilation needs of the forum mezzanine (which hosts special events), AHU-1 is intended to serve the routine need of other spaces of the building.

To manage the development scope considering diverse building features, we have chosen four specific spaces within the TI building for the virtual tour development. Three spaces are open to general occupants, in particular, the study room studios for students and teachers, the forum mezzanine for guests to the events, and the conference room for the staff. The mechanical room, the fourth space, is intended for engineering students to understand HVAC systems. These spaces are further elaborated as follows.

- Study room studios (400 m^2, capacity: 95 people). This space comprises three studios that can be flexibly separated or combined using movable partitions for traditional or active learning classrooms. Located on the first floor, heating is provided through a single-row heating element at the building's perimeter and the in-slab floor heating.

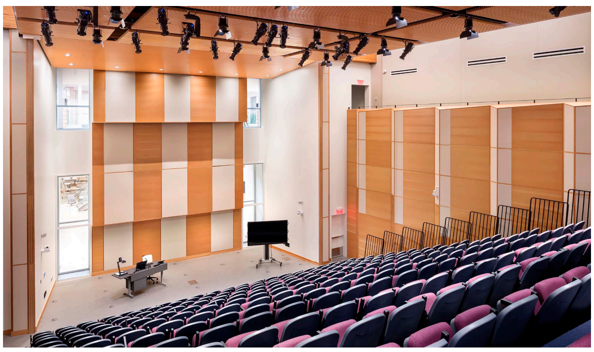
Cooling is facilitated by in-slab floor cooling and chilled beams. The ventilation function is fulfilled by a mixed-air system.

- Forum mezzanine (380 m^2, capacity: 132 people for dining and 336 people for stadium seating). This space is intended for special events, and it can be configurated for dining or stadium seating. It features a high ceiling spanning about two floors in height. Space conditioning is achieved through an individual air handling unit (AHU-2) employing the all-air configuration with supply floor diffusers and return air grilles close to the ceiling.
- Conference room (45 m^2, capacity: 16 people). Located on the second floor, this space is conditioned by air from supply floor grilles with ducted fan coils providing both heating and cooling, along with radiant panels for heating.
- Mechanical room (250 m^2). Located in the basement, this space houses the major mechanical system components of the building, including two AHUs, plate heat exchangers (to interface hot and chilled water from the district energy system), and pumps for the hydronic system.

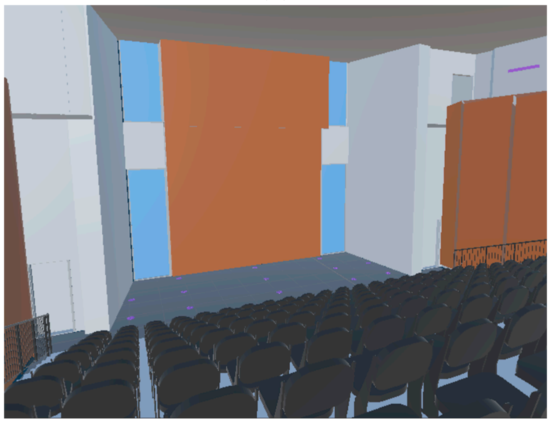
In the development of the virtual environment, we start with the 2D drawings and 3D models of the TI building (created in Revit), which provide the basic geometry and architectural features of the building's spaces for the virtual tours. We then incorporate the HVAC and interior components into the virtual spaces. For example, Figure 1 displays photos of one study room studio, the forum mezzanine with stadium seating, the plate heat exchanger in the mechanical room, and their corresponding virtual renderings.

(**a**)

(**b**)

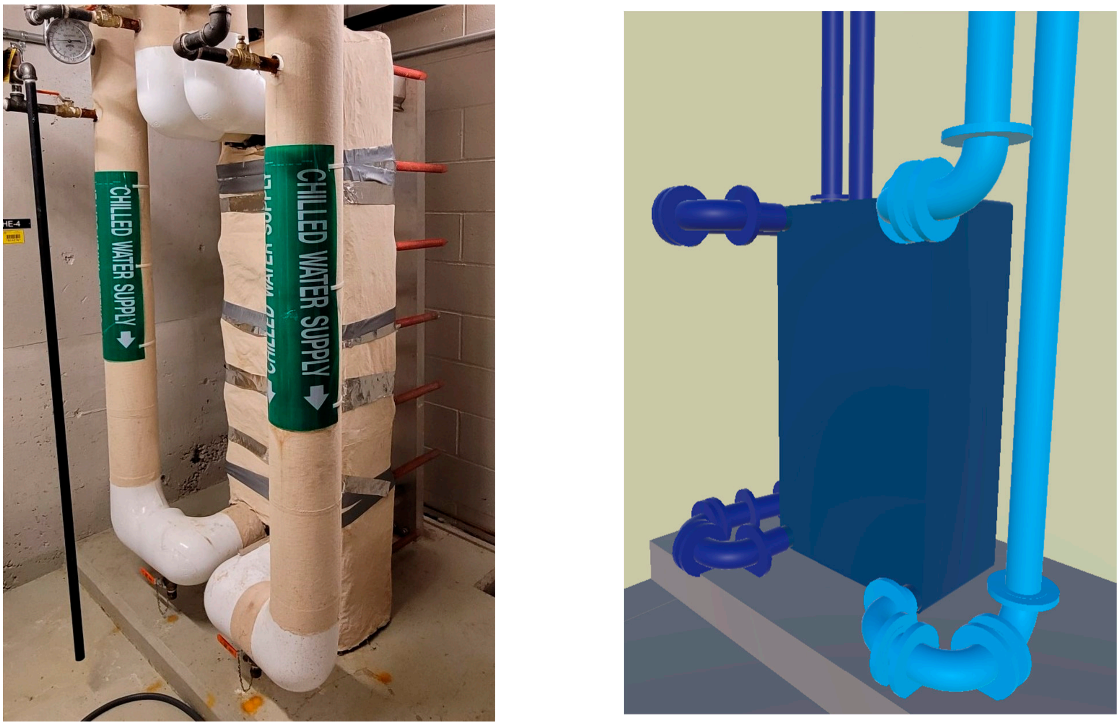


(**c**)



(**d**)

Figure 1. *Cont.*

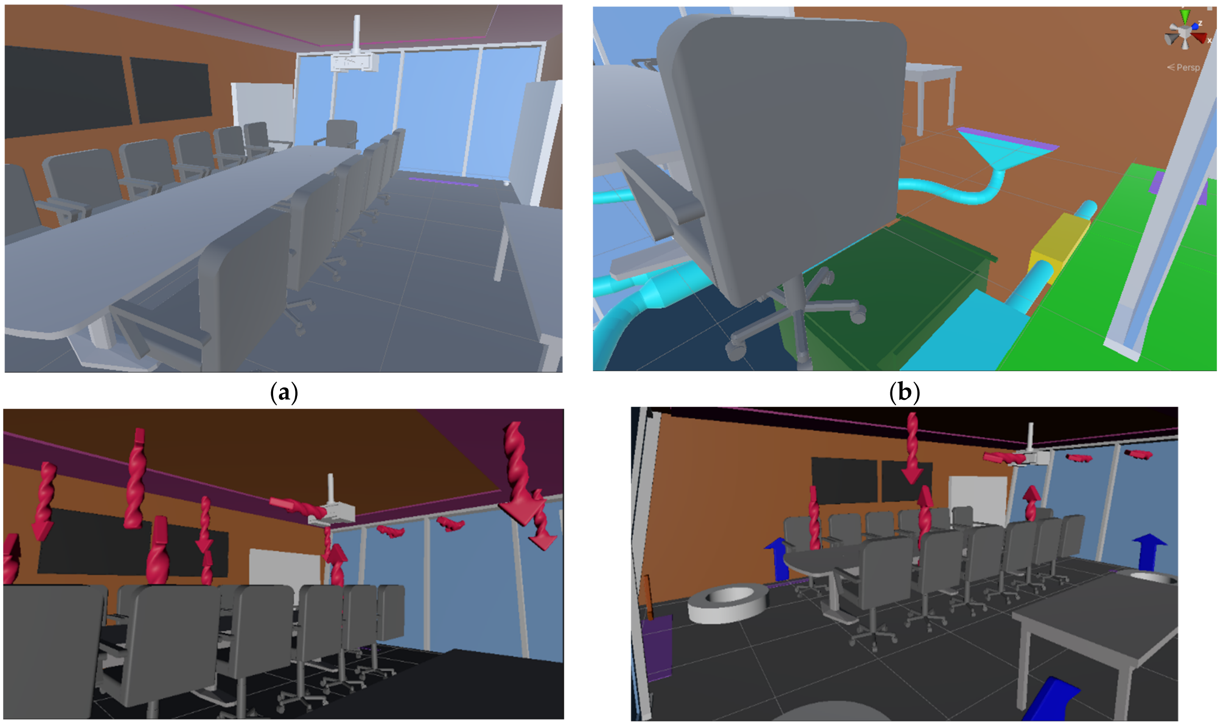


(**e**) (**f**)

Figure 1. Illustration of physical and virtual spaces. (**a**) Photo of one study room studio (Studio C); (**b**) screenshot of virtual space of Studio C; (**c**) photo of the forum mezzanine in stadium seating; (**d**) screenshot of virtual space of the forum mezzanine; (**e**) photo of the plate heat exchanger in the mechanical room; (**f**) screenshot of the virtual plate heat exchanger space.

Then, we export the building information from Revit as an OBJ file, which is imported into Unity to design the virtual tours. The virtual tours, developed in Unity, are subsequently exported to HoloLens 2, which serves as the head-mounted display for delivering the virtual tours to users. It is worth noting that other head-mounted displays for pure virtual reality experiences could be utilized in our case. However, HoloLens 2, which supports mixed reality, was chosen due to its availability in our school's makerspace. Let us take the conference room and the forum mezzanine as examples to illustrate some scenes of the virtual tours.

Figure 2 provides four screenshots to illustrate typical visuals of the conference room in the virtual tours. Figure 2a shows the view from the entrance of the conference room, allowing users to freely move their heads to explore the space. The virtual environment enables us to display ductwork and HVAC components that are not visible to users in the physical space. For example, Figure 2b displays the fan coil unit (in dark green) responsible for supplying heating/cooling air. Different types of arrows are employed to annotate various types of heat flows. For example, Figure 2c depicts a heating mode condition, with arrows indicating (1) heat loss through windows, (2) internal heat gains, and (3) heating from radiant panels. Figure 2d showcases a cooling mode condition, where blue arrows represent cooling air. Voice guidance is incorporated into the virtual tours to direct users' attention and provide contextual information. The type of contextual information includes the purpose of the space, the functions of HVAC systems in the heating/cooling modes, the terminology of HVAC components, and the meanings of animated arrows. The virtual tour of the conference lasts approximately 9 min without pausing by users.

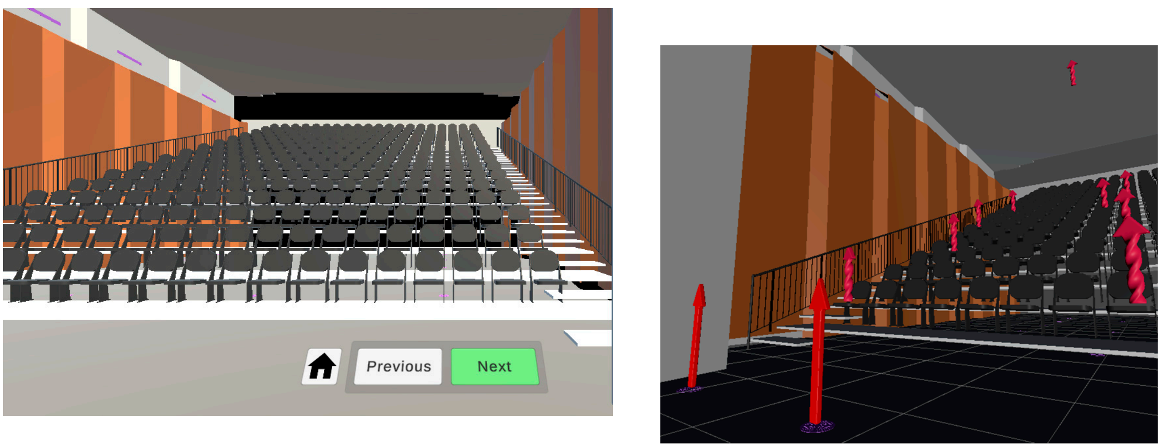


(**a**) (**b**)

(**c**) (**d**)

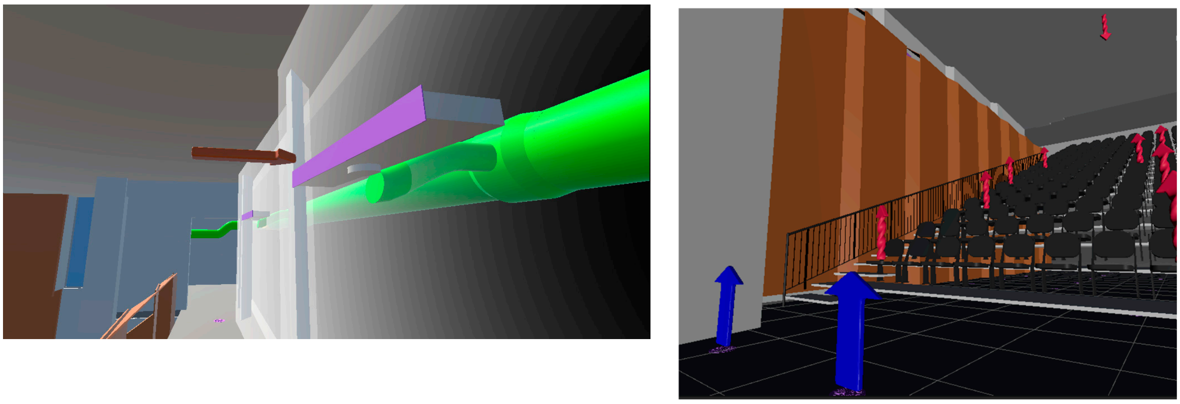
Figure 2. Screenshots of the virtual tour of the conference room. (**a**) Entrance view; (**b**) ductwork and fan coil; (**c**) heating mode; (**d**) cooling mode.

Figure 3 provides four screenshots illustrating the virtual tours of the forum mezzanine. In Figure 3a, users perceive the stadium seating upon entering. Three buttons (i.e., home, previous, and next) are positioned at the bottom for users to navigate different scenes of the virtual tours. Figure 3b depicts a heating mode condition with internal heat gains (indicated as wavy red arrows) from the seating area, while heating supply air is distributed from the floor diffusers. Figure 3c showcases the return air illustrated by an arrow (brown), along with wall-mounted return grilles and a return air duct (green) positioned at the top portion (close to the ceiling) of the room. The cooling mode concept in Figure 3d mirrors the heating mode, with supply air (blue arrows) intended for cooling. The virtual tour of the forum mezzanine lasts approximately 9 min without pausing by users. The corresponding lengths of the virtual tours of the study room studios and the mechanical room are 10 min and 11 min, respectively.



(**a**) (**b**)

Figure 3. *Cont.*



(**c**) (**d**)

Figure 3. Screenshots of the virtual tour of the forum mezzanine. (**a**) Entrance view with stadium seating; (**b**) heating model; (**c**) return air; (**d**) cooling mode.

After developing the virtual tours of the four spaces, we proceed to examine the acceptance and efficacy of these tours through a survey study, which will be discussed in the next section.

4. Survey Study

As mentioned in Section 3, the virtual tours are intended for two audience groups: engineering students and general occupants. When we conduct the survey study, we focus on the second group (i.e., general occupants), where we can invite different people to participate in the virtual tours and the survey. Through the survey study, we want to examine (1) the acceptance of VR technology and (2) the efficacy of VR tours for understanding the built environment. This section will discuss the design of the survey study and the results.

4.1. Survey Design and Data Collection

In the design of the survey study, we plan to limit the time required for the virtual tours and the completion of the survey to within 30 min. Considering the virtual tours of four spaces discussed in Section 3, we select the virtual tours of the forum mezzanine and the conference room, and skip the mechanical room and the study room studios. We skip the mechanical room because its content is too technical for general occupants, and we skip the study room studios to save the participants' time in the survey study.

The survey instrument consists of thirteen (13) multiple-choice questions divided into three sections. The first section comprises two questions, which inquire about the participants' experience with HVAC systems and VR technology (ranging from limited to highly experienced). The second section consists of six quiz-type questions to examine how well the participants can acquire information from the virtual tours of the forum mezzanine and the conference room. The third section contains five questions concerning the participants' personal opinions of the virtual tours.

The general procedure of each survey session is designed as follows. First, after briefing the purpose of the survey study, we distribute the head-mounted devices (i.e., Microsoft HoloLens 2 in our case) to participants and instruct them on initiating the virtual tours. Participants can then take the virtual tours individually at their own pace, with technical support provided if they encounter issues with the VR devices. After completing the virtual tours, participants are invited to fill in the survey.

To recruit participants, we have reached out to four groups of people: students in an HVAC class, recent engineering graduates, staff from the university's Office of Sustainability, and industry professionals from an enterprise software development business. The university's ethics approval for this study was obtained on 27 October 2023 (ID: RED23-1417). The data collection for the survey study took place from November 2023 to January 2024, resulting in survey results collected from 34 participants (n = 34).

Due to the limited number of VR devices (about eight devices available at one time) and the availability of different participants, we conduct the survey in multiple sessions. For the workflow of each survey session, we allocate 5 min for the opening and distribution of the VR devices. While participants can pause and repeat the virtual tours at their own pace, they generally take about 20 min to complete the two virtual tours. Subsequently, they spend about 5–10 min completing the survey.

4.2. Discussion of the Survey Results

We conduct a statistical analysis of the survey results in two parts. In the first part, numerical summaries of the survey results are provided to directly examine the acceptance of VR technology (related to Q9 to Q13) and the efficacy of VR tours (related to Q3 to Q8). In the second part, a correlation analysis is run to explore how the backgrounds of the participants may be associated with the acceptance and efficacy of the VR tours.

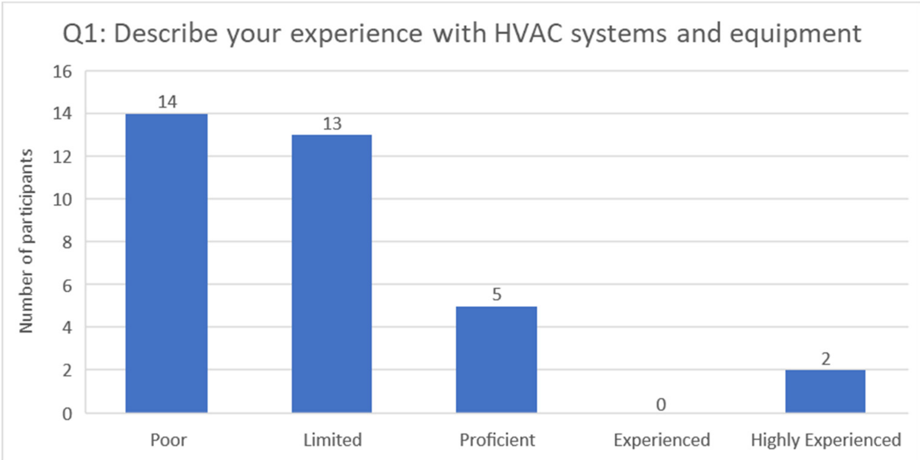
As discussed earlier, the backgrounds of the participants are quite diverse, ranging from engineering students to working professionals in sustainability or the software industry. Instead of collecting demographic information, we only inquire about their own perception of their experiences with HVAC systems (Q1) and VR technology (Q2). The results are shown in Figure 4. As observed, most participants consider themselves as having "poor" or "limited" experiences with HVAC systems (27 out of 34) and VR technology (25 out of 34). As an observation, while the low-level experience with HVAC systems is understandable (as it is relevant to a professional industry), we might have expected that more participants would have had some experience with VR. In particular, VR/AR technology has become more common in social media and gaming.

To examine the efficacy of the VR tours, the next six questions (Q3 to Q8) on the survey are quiz-type questions, asking participants to recall information from the virtual tours. The average (μ) of the quiz results is 2.6 out of 6 (with a standard deviation, $\sigma = 1.3$). Admittedly, we expected higher quiz scores from participants. While this quiz average is considered unsatisfactory, we will investigate further to identify possible explanations later in this paper.

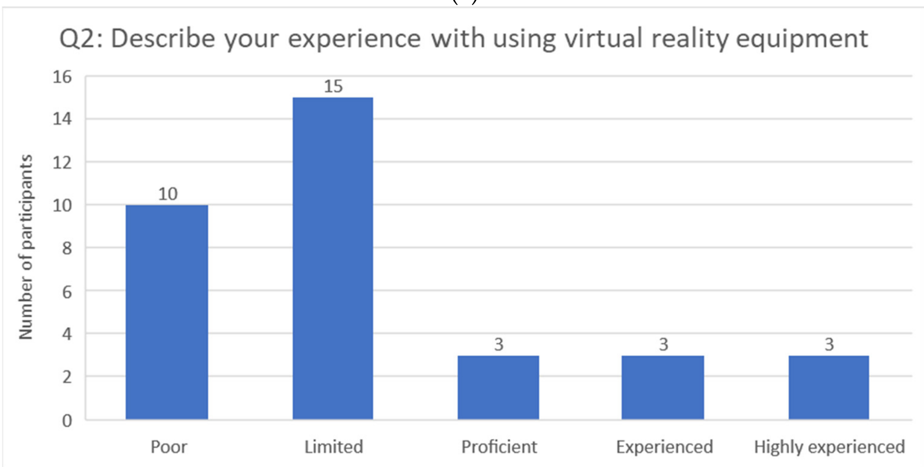
To examine the acceptance of VR technology, a five-level Likert scale is used for the participants' responses, with 1 point for "strongly disagree" and 5 points for "strongly agree" in Q9 to Q13. The average and standard deviation values of these questions are provided in Table 1. Overall, Q13 indicates that participants are satisfied with the virtual tours (average score: 4.3 out of 5). Additionally, the number of participants indicating "(4) agree" and "(5) strongly agree" is considerably higher than the number indicating "(1) strongly disagree" and "(2) disagree". These results generally support that the participants welcome VR technology for learning the built environment.

For further interpretation, Q9 and Q10 (average scores: 3.7 to 3.8 out of 5) are relevant to opinions about the HVAC content, while Q11 and Q12 (average scores: 4.1 to 4.2 out of 5) are relevant to opinions about VR technology. Observing the difference in these scores, we should note that participants tend to favor the VR experience more than the HVAC content from the virtual tours. Together with the "quiz" scores (Q3 to Q8), learning HVAC content from the virtual tours is an aspect that needs strengthening in the future.

In the second part of the statistical analysis, we conduct a correlation analysis of six groups of survey questions. These groups are formed to investigate correlations associated with HVAC vs. VR and the comparison of prior experiences, quiz results, and opinions. In particular, the first two groups are relevant to the participants' experience with HVAC (Q1) and VR (Q2), respectively, which are treated as separate personal factors in the analysis. The third group relates to the quiz results (Q3 to Q8), which measure the information retention from the VR tours. The fourth and fifth groups are relevant to the participants' opinions about the VR tours relative to HVAC content (Q9 to Q10) and VR application (Q11 to Q12), respectively. The sixth group is concerned with the overall impression of the VR tours (Q13). The correlation values of these six groups are provided in Table 2. For clarity in the discussion, let *r*(Qx, Qy) represent the correlation value between questions Qx and Qy (e.g., *r*(Q1, Q9–Q10) = 0.09 according to Table 2).



(**a**)



(**b**)

Figure 4. Experience levels of participants with HVAC systems and VR technology. (**a**) Survey results with HVAC experience; (**b**) survey results with VR experience.

Table 1. Summary of survey scores of Q9 to Q13.

	Average (μ)	Standard Deviation (σ)	Number of "Disagree" (1 or 2)	Number of "Agree" (4 or 5)
Q9: The tour made me feel confident about the functions of the air-distribution and hydronic systems throughout the building.	3.7	1.0	2	22
Q10: The commentary provided throughout the tour was helpful in my understanding of the HVAC systems.	3.8	1.0	4	25
Q11: The virtual reality user interface was easy to navigate.	4.1	0.8	2	28
Q12: The VR technology and equipment was appropriate for the applicability of the building tour.	4.2	0.9	1	28
Q13: My overall appreciation of the virtual reality tour and technologies was positive.	4.3	0.9	2	30

Table 2. Correlation values of six groups of survey questions. Light gray entries are related to prior experiences of users; yellow entries are related to quiz results; green entries are related to participants' opinions.

	Experience with HVAC (Q1)	Experience with VR (Q2)	Quiz Results (Q3–Q8)	Opinions on HVAC Content (Q9–Q10)	Opinions on VR Application (Q11–Q12)	Overall Impression (Q13)
Q1	1					
Q2	0.02	1				
Q3–Q8	−0.21	0.18	1			
Q9–Q10	0.09	0.33	−0.04	1		
Q11–Q12	0.17	0.26	0.25	0.55	1	
Q13	0.12	0.17	−0.05	0.77	0.61	1

Concerning prior experiences (light gray entries in Table 2), we first note that the correlation between HVAC and VR experiences is weak (i.e., r(Q1, Q2) = 0.02). We interpret that these two variables are relatively independent. As an observation, it seems that participants with more VR experience tend to enjoy the virtual tours more than those with more HVAC experience, based on the correlation values of Q9–Q10 (0.09 vs. 0.33), Q11–Q12 (0.17 vs. 0.26), and Q13 (0.12 vs. 0.17). Nevertheless, these correlation values are not high in general (highest at r(Q2, Q9–Q10) = 0.33). We interpret that the experience levels in HVAC or VR are not influential for people to participate in virtual tours.

Regarding the quiz results (yellow entries in Table 2), it is interesting to note that participants with more VR experience tend to achieve better quiz results (r(Q2, Q3–Q8) = 0.18), while the corresponding correlation with HVAC experience is negative (r(Q1, Q3–Q8) = −0.21). That is, participants with more HVAC experience tend to achieve lower scores in the quiz questions. We should also note that the quiz results (Q3–Q8) are not strongly correlated with other aspects (highest at r(Q3–Q8, Q11–Q12) = 0.25). This implies that the content of the virtual tours and the quiz questions can be further improved so that participants can enjoy and learn from the virtual tours.

Regarding participants' opinions (green entries in Table 2), while participants are generally positive about the virtual tours (as indicated in Table 1), their opinions about HVAC content, VR application, and overall impression are positively correlated (e.g., correlation values from 0.55 to 0.77). This may imply that despite the weak quiz results, participants generally welcome the virtual tours as an approach for them to learn about the built environment.

4.3. Participants' Comments and Overall Implicaitons

Beyond the survey data, we also asked participants for their written and verbal comments after the virtual tours. In this section, we will consider their comments alongside observations from the survey results (discussed in Section 4.2) to examine our virtual tour development holistically, highlighting pros and cons.

On the positive side, one outstanding comment is the engagement factor, where participants generally found the virtual tours interesting and engaging. This sentiment is also reflected in the moderately high scores in the opinion-type questions (Q9–Q13) (see Table 1). This corresponds to literature findings suggesting that AR/VR technology can effectively engage students and participants in their learning process. For example, the use of AR/VR technology can promote student engagement in the context of safety training [13,14] and spatial skill training [31]. The study by [40] demonstrated how AR technology (i.e., Augmented Book) can promote student motivation.

Additionally, some comments noted that the transparency feature (e.g., Figure 3c) helps participants visualize and relate "unseen" HVAC components in the building spaces. The presence of arrow annotations denoting various heating, cooling, and ventilation aspects proved helpful for understanding the functions of different air distribution and hydronic systems. This corresponds to developments of other researchers that utilize "unseen" elements in the real context to support learning such as showing AR arrows as loading and reaction forces in structural analysis [34] and superimposing AR meshes of finite elements to illustrate stress distribution of a real object [35]. Furthermore, participants enjoyed the option to physically move around the virtual space while still maintaining a large field of view by walking and turning within their surrounding environments.

On the negative side, the voice guidance of the virtual tours may have confused some participants to distinguish differences in HVAC systems between the forum mezzanine and the conference room. One possible reason is the repetitive and similar terminologies used in describing the HVAC systems in both spaces. This observation could explain the low scores in the quiz questions (Q3–Q8). In retrospect, the virtual tours could be seen as another form of one-way lecturing in terms of content delivery, making it challenging for participants to absorb the information. This learning challenge may not be effectively addressed solely by immersive graphical information. Additionally, for participants with lower prior experience with VR, handling the learning of both VR and HVAC content simultaneously could introduce another learning challenge.

To reduce the "one-way lecturing" effect, one idea is to minimize the use of voice guidance to control the information flow of the VR tours. For example, after explaining a concept (e.g., ventilation), the VR tours can prompt quiz questions to reinforce the new learning. This idea is similar to game-based learning [41,42], where participants can control the timing of quiz questions and feel a sense of accomplishment after completing them. In fact, some participants, in their verbal comments, have suggested adding quiz questions during the VR tours rather than after them. In addition, text labels can be added to key HVAC components in the VR tours so that participants do not solely rely on voice guidance to remember new terminology from the VR tours.

For future development, we recognize that applications of AR/VR for training and learning require collaboration across three distinct aspects of knowledge and skills, elaborated as follows:

- Information technology: The delivery formats of AR/VR technology limit what can be achieved in designing the learning experience. As AR/VR technology evolves rapidly, experts in AR/VR can assist trainers and educators in selecting and deploying suitable tools for specific training and learning purposes.
- Domain knowledge: For education and training, domain knowledge (e.g., HVAC content) itself could be complex. In this case, domain experts not only provide content information but also organize the structure of knowledge content and prioritize the relevance and importance of information so that trainees or students can acquire essential information.
- Pedagogy: How students learn is not a trivial question. For our virtual tours, we can enhance them by providing more interactive activities for learning. How to prompt supportive information (e.g., visual or vocal) and questions (i.e., problem-based learning) can affect the effectiveness of learning from the AR/VR experience.

5. Conclusions

This paper documents the design, development, and deployment of virtual tours for a university building. These virtual tours aim to assist engineering students and general occupants in visualizing the functioning of mechanical systems in buildings. In design and development, we utilize existing 3D models in Revit and engineering drawings to create the scenes of four spaces (i.e., study room studios, forum mezzanine, conference room, and mechanical room) using Unity. The education content focuses on how a space is heated, cooled, and ventilated in winter and summer seasons through hydronic and air distribution systems. To evaluate the acceptance of the virtual tours by general occupants, we have conducted a survey study with 34 participants (n = 34). On a positive note, participants generally appreciated the virtual tour experience (4.3 out of 5 in Q13) and considered VR appropriate for understanding a building (4.2 out of 5 in Q12). However, due to the weak quiz results (Q3 to Q8), the virtual tours still need improvement to help participants acquire HVAC content.

As the authors of this paper are all from mechanical engineering backgrounds, we want to echo the discussion of the "accessibility of AR/VR systems" in [9] (p. 18), stating that teachers "with only an AEC or educational background" can find the development of AR/VR experiences challenging. While information and computer experts can demonstrate the availability and functionality of different AR/VR tools, teachers still need ideas and insights to design how students can interact with virtual content for learning. We envision that all information, subject-domain, and pedagogy experts would need to collaborate closely to advance AR/VR experiences for learning. Based on the experience from this research, our future work has two directions:

- Direction 1: One limitation of this study is the use of Microsoft HoloLens 2, which is not an economical device for general occupants. Targeting general occupants in understanding the built environment, one plan is to explore other tools that are more flexible and scalable than Microsoft HoloLens 2 for deployment. Examples include AR apps (which occupants can run on their mobile devices and check AR-based annotations) and H5P (where virtual tours can be packaged and deployed on websites).
- Direction 2: Another limitation of this study is that the learning effect from quiz questions is limited. One direction of improvements is to implement quiz questions and text labels in the VR tours to reinforce the new learning. Further, understanding the built environment involves interpretation of industry and scientific concepts in physical space (e.g., definition of ventilation, concept of thermal comfort). One plan is to study strategies to integrate both virtual and in-person experiences to gain a holistic understanding of the built environment. For example, Maltais and Gosselin [39] (p. 1022) have discussed that virtual tours cannot (and should not) replace in-person visits. How to integrate both virtual and in-person experiences in learning is an open question in our future work.

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