Towards Immersive Virtual Environments using 360 Cameras for Human Building Interaction Studies

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ABSTRACT

Virtual Reality has been growing in popularity and demand as technology has been substantially improved and become more readily available to the general public in the recent years. Similarly, the Architecture, Engineering and Construction industries have benefited from these advances and extensive research has been performed to adopt and streamline its utilization. An example of this adoption has been the use of Immersive Virtual Environments (IVE) as a representation of the built environment for different purposes such as building design and occupant behavior studies in the post construction stage – i.e., Human Building Interaction.

This research has investigated a workflow for different alternatives of reality-capturing-based technologies that have been tested to generate a more realistic representation of the built environment regarding HBI. One of these alternatives considered was 360-image based IVEs. This alternative in particular was tested and compared by the means of a preliminary user study in order to evaluate whether it is an adequate representation of the built environment regarding HBI, and how it is compared to commonly used benchmarked Graphical based IVEs. Ultimately, participants of this user study reported a strong feeling of immersion and presence in the 360-image based IVE and showed a better performance in cognitive tasks such as reading speed and comprehension. In contrast, participants showed a better performance in object identification and finding in the Graphical based IVE. The results of our preliminary user study indicate that 360-image based IVEs could potentially be an adequate representation in the study of Human Building Interaction based on these metrics. Further research with a larger sample size should be performed in order to generalize any findings.

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GENERAL AUDIENCE ABSTRACT

Virtual Reality has been growing in popularity and demand as technology has substantially improved and become more available to the general public in the recent years. Similarly, the Architecture, Engineering and Construction industries have benefited from these advances and extensive research has been performed to utilize this technology.
An example of this adoption has been the use of Immersive Virtual Environments (IVE) as a representation of a building for different purposes such as design and understanding of the way occupants interact with a building. IVEs rely on using special digital goggles (called head mounted displays or HMDs) that help users immerse in a virtual environment and experience it. For this reason, our research has sought to explore different alternatives to possibly generate a more realistic immersive virtual environment that relies on immersive image-based technologies to test how humans behave, respond, and interact with a building. One of these alternatives considered was 360-degree cameras and their associated images. We sought to study whether these technologies provide an improved experience for users compared to the environments that are created through computer graphics.

This thesis explains the processes that were investigated to understand the creation of an IVE, and the different alternatives available in the market to generate a 360-degree image based IVE. Then, one of these alternatives was tested and compared to a classic IVE through an experiment in order to evaluate whether 360-degree image based IVEs can be an adequate representation for building occupant interaction studies.

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1. Introduction

Human-Building Interaction (HBI) is defined as the research area that investigates how humans interact with the built environment and how these interactions affect them. Humans are subjected to different interactive opportunities that could shape the physical, spatial and social characteristics of the built environment [2, 3]. Research studies that investigate the interaction between humans and the built environment are increasingly relying on immersive virtual representations of the physical environment in order to gain a better understanding of human behavior and their responses to designed or existing environments. However, according to various studies, the AEC industry still has a big area of improvement regarding the utilization of VR technology in the building design, and post construction stage; in which HBI and occupant behavior play a very important role [4]. For this matter, Immersive Virtual Environments (IVEs) have been utilized to generate a representation of the built environment in order to improve the design-review process, and ultimately the building occupant interaction with the built environment, which is referred to as user-centered design [1, 5]. Therefore, it is important to determine whether IVEs are an adequate representation of the built environment for human-building interaction studies.

IVEs are virtual representations of physical spaces in which users navigate and interact, typically, through the use of hardware such as Head Mounted Displays (HMDs) [6]. According to Slater and Wilbur [7], IVEs are virtual environments that must generate a sense of immersion and presence in their users. Immersion is defined as the extent that the technology is able to deliver an "inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant" [7]. Alternatively, presence is defined as the psychological state in which the user enters when interacting with the virtual environment [7]. Virtual Reality in general has been growing in popularity and demand as the technology in both hardware and software has substantially improved and become more readily available to the general public. In the same fashion, the Architecture, Engineering and Construction industries have benefited from these advances; and extensive research has been performed in recent years to streamline its utilization within the industry [8-10] . Some specific areas in the AEC industry in which VR adoption has grown significantly are education [11-13], safety [14-18], building design [1, 8, 19-21], preconstruction planning [22], remote collaboration [10, 23-26], and Human-Building Interaction (HBI) [1, 4, 20, 27]. Specifically, the development and testing of different IVEs regarding Human-Building Interaction are the main focus of this research. More specifically, this research seeks to evaluate image-based reality capturing technologies that could potentially enable a more realistic representation of the environments considering the possibility of mixing imagery and graphical objects together, such as 360-degree panoramic images or point clouds.

The process of obtaining as-built information of the built environment (reality capturing) has traditionally relied on the use of devices such as 3D laser scanners or digital single-lens reflex (DSLR) cameras[28] [6]. However, the utilization of different devices, namely 360-degree cameras, for this purpose has gained interest in recent years. Based on the data obtained with these types of equipment, whether it is point cloud files or just regular images, modeling algorithms can generate 3D models of the built environment to reflect its exact features for different purposes. In order to process the data obtained into a 3D model, there are a variety of software packages that possess this capability such as: Matterport [29], Agisoft Metashape [30], Cupix [31]. Pix4D Mapper [32], etc. These models are particularly useful in a wide array of applications for different purposes such as: architectural reconstruction [33, 34], architectural presentations [35], cultural heritage [34], interior design [19], real estate [36], virtual tours [37, 38], etc. Virtual tours are examples of an Immersive Virtual Environment (IVE). For this reason, this research has intended to develop and test out different alternatives of generating an IVE starting from the reality capturing stage to the visualization of an IVE. This was based on our hypothesis that reality-capturing based technologies could provide a more realistic experience for users and improve their interaction performance. To investigate this hypothesis, as noted, this research evaluated different alternative technology pipelines that could enable realty-capturing-based IVEs. By identifying the capabilities and shortcomings of the components in each pipeline, we identified one alternative to be investigated for its capabilities in facilitating user interactions. The reaming sections of this thesis are as follows. Section 1.1 and 1.2 describe different modes of IVE and the technologies that are used to develop them. In Section 1.4, we have described the efforts to evaluate different pipelines. Sections 4 to 9 describe the selected technology, the questions to be answered with respect to user interaction studies, and the procedure and findings of a preliminary data collection and analysis process.

1.1 Immersive Virtual Environment Development

The development of IVEs can be separated into two different categories: panorama-based immersive VR and immersive VR [38]. When utilizing a panorama-based immersive IVE, the level of interactivity and immersion is usually not as strong compared to that of an immersive VR IVE. The weaker feeling of interaction and immersion is due to the fact that it is not possible to move anywhere around the environment with complete freedom, given that the virtual environment is comprised of different spherical panoramas, and the movement within the environment is restricted to the location where the panoramas were specifically taken. These particular locations are called “hotspots” and they can be placed either manually or automatically, depending on the software that is being utilized to create the IVE. Some examples of immersive panorama-based software programs are Matterport, 3D Vista and Cupix.

On the other hand, immersive VR is usually developed utilizing Building Information Modeling (BIM) authoring software programs that allow the integration of different interactive elements in the virtual environment. These interactive elements usually provide a higher level of immersion and presence to the user, but it depends on the quality of the graphics that both the software and hardware (HMDs and/or PC) provide to the user when interacting with the IVE. Good quality graphics for VR require high computer processing power to be realistic enough, and to run properly without any sort of lag or delay. Some examples of the most popular immersive VR softwares are: Enscape, Unity 3D, and Unity Reflect Review.

1.2 Virtual Reality Hardware

Recent computational technology development has positively impacted the Virtual Reality world. Head-Mounted Displays (HMD) have recently evolved to include powerful features that allow users to have a smoother and therefore, more immersive experience. Some examples of recently released HMDs are the Oculus Quest 2 [39], Oculus Rift [40], HTC Vive Pro [41], Windows Mixed Reality [42], etc. These devices can be utilized to visualize an IVE and present the generated 3D models for different purposes and audiences, such as potential clients or stakeholders of a project. HMDs are generally divided in two different categories: tethered and standalone. Tethered HMDs have wires attached to them, and they are required to be plugged into a PC in order to run. For this reason, tethered HMDs are often more powerful in computer processing. However, these wires limit mobility and could make the user to feel restrained, and therefore, less immersed in the IVE. Some examples of tethered HMD's are the HTC Vive Pro, Oculus Rift and Windows Mixed Reality. On the other hand, a standalone HMD does not have wires attached to it, and it is powered by a lithium battery. For these reasons, standalone HMDs are usually more economically accessible for the general consumer. A few examples of the most popular standalone HMDs are: Oculus Quest 2 and HTC Vive Focus.

1.3 360-Degree Technology

As technology has developed in the recent years, 360-degree cameras have evolved with it to produce better quality images with more accessible and advanced devices compared to those of previous years. 360-degree cameras are sensors that are able to automatically generate a spherical panorama. A spherical panorama is defined as an image obtained by stitching a series of photographs that share the same point of view [38]. Regular DSLR cameras can produce panoramas as well, but manual processing with specialty software programs is needed in order to stitch those images together to create a spherical panorama [6]. In the same fashion, the utilization of simpler and lower priced sensors such as smartphone cameras has been investigated recently to evaluate whether they could be used for the same purpose [43]. With this being said, 360-degree cameras could be a feasible alternative for reality capturing when time and efficiency constraints are an important factor, since no manual processing to stich the images together is needed. Table 1, obtained from Barazzetti et al., compared the cost of some of the different 360-degree cameras available at that time (February 2018), and it was adapted by adding the current market cost, and the still image resolution of each one of them [33]. It is important to mention that 3 years later, most of the more expensive cameras presented in Table 1 below have been discontinued due to their higher price tags and low market demand. A possible reason for this could be because of newer cameras available, with better quality for a more accessible price tag to the general consumer.

Table 1. 360-Degree Cameras Available in the Market

360-degree Camera	February 2018 Price (EU)	August 2021 Price (USD)	Photo Resolution
Samsung Gear 360	90	NA*	15 MP
Garmin VIRB 360	800	800	15 MP
Insta 360 Air Voor	140	NA	4 MP
Nikon KeyMission 360	350	300	24 MP
Xiaomi Mijia Mi Sphere 360	220	145	24 MP
LG 360	150	100	16 MP
360FLY	750	500	8 MP
Samsung New Gear 360	300	140	15 MP
Ricoh Theta V	430	530	14 MP
Ricoh THETA S	350	300	14 MP
GoXtreme Dome 360	90	100	4 MP
Sansnail V1	65	NA	5 MP
YI VR 360	400	300	12 MP
Motorola Moto 360	290	40	13 MP
Gopro Odyssey	12200	NA	64 MP
Videostich Orah 4i	2900	2200	13 MP
Gopro Omni	4000	3500	31 MP
Nokia OZO	49000	NA	32 MP
Sphericam 2	1350	NA	50 MP
Insta360 Pro	3600	5500	59 MP

* NA: Not Applicable or Not Available

For the purpose of this research, 4 of the most popular 360-degree camera options available in the market at the time were selected for two categories: Specialty and Commercial grade. Table 2 below illustrates the market cost, and resolution of each one of those 360-degree cameras.

Table 2. 360-degree cameras available in the market in 2021

360-degree Camera	August 2021 Price (USD)	Photo Resolution	Category
Ricoh Theta SC2	300	14 MP	
Insta360 ONE X2	440	18 MP	
Insta360 ONE R	480	19 MP	Commercial
Ricoh Theta Z1	1045	23 MP	
Matterport Pro2 3D	2800	134 MP	
Insta360 Pro 2	5000	59 MP	

1.4 Initial Research Objective

As previously mentioned, our initial objective is to evaluate different image-based reality capturing technologies that could potentially enable a more realistic representation of the built environments, with the purpose of testing human building interaction. For this reason, based on our experience interacting with the different devices and software, we have determined a workflow that goes from the reality capturing initial stage to the IVE visualization stage The proposed workflow and framework for IVE generation are shown in Figure 1 and 2, respectively:

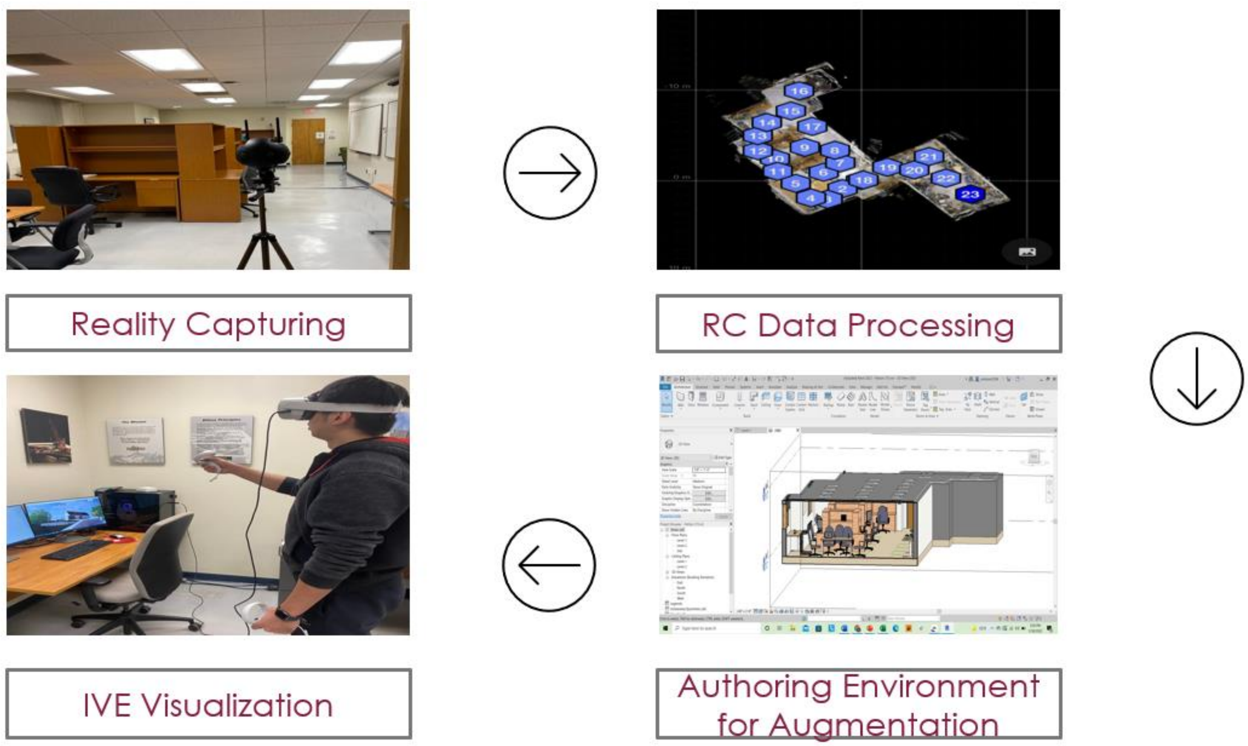

Figure 1. Workflow for Immersive Virtual Environment Generation

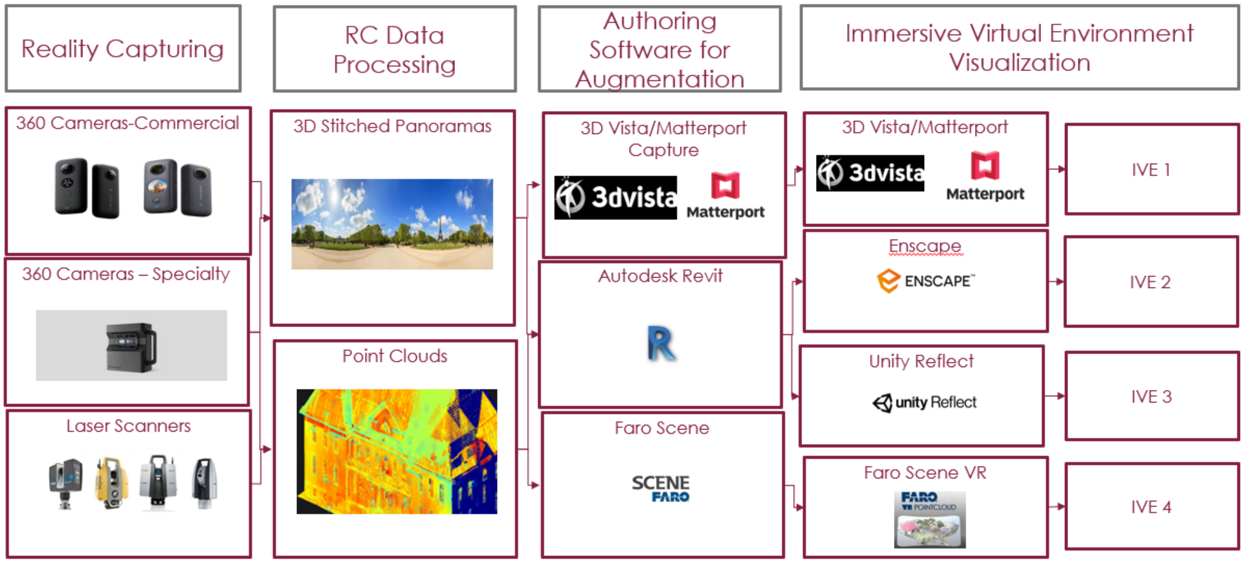

Figure 2. The general framework for Immersive Virtual Environment Generation

The framework presented in Figure 2 above, consists of 4 different stages that have been identified in the workflow of generating an IVE of the built environment. Previous research has investigated similar workflows with different stages that also go from the reality capturing to the IVE visualization stage. For instance, Smith suggested a workflow that utilized high-resolution digital photographs captured with a DSLR camera. The objective of this workflow was to establish a 5-stage process to create an image based IVE that could serve for the purpose of behavioral research in built and natural environments [6]. The difference of this workflow from the one we have developed lies on the number of stages, given the fact that by utilizing a DSLR cameras adds an extra image processing stage to convert regular images to a spherical panorama. Moreover, our workflow focuses on 2 different reality capturing devices such as 360-degree cameras and laser scanners.

The first stage in our workflow consists in Reality Capturing (RC) with different types of devices. As previously mentioned, two different categories of 360-degree cameras have been established for this stage. 360-degree Specialty cameras are labeled as such for the higher resolution quality they provide, and the retail price that they can be acquired for; in contrast to the Commercial grade cameras which are more accessible to the general consumer but offer lower resolution in general. The second stage is the RC Data Processing stage. Two different types of data can be generated with these devices: 360-degree pictures also known as 3D stitched panoramas, and point clouds. Thirdly, this data can be processed into different software packages depending on its type. For instance, 3D stitched panoramas can be processed for augmentation utilizing software like 3D Vista, Cupix and Matterport Capture [44, 45]. On the other hand, point cloud data can be processed into software with those capabilities such as Autodesk Revit and SketchUp [46] . Lastly, once the geometry has been modeled and augmented to a certain degree, it can be visualized in the form of an Immersive Virtual Environment (IVE) using software with this capability such as: Unity 3D, Unity Reflect, Matterport, Enscape, 3D Vista, etc [47] . For the purpose of our research, we have experienced and tested out 5 different alternatives for the generation of an IVE. These different alternatives were the following:

Table 3. IVE Generation Alternatives

Alternative	**Reality Capturing Device**	**RC Data Processing**	**Authoring Software for Augmentation**	**IVE Visualization**
1	360-Degree Specialty Camera - Insta 360 ONE X2	Point Cloud - Pix4D Mapper/Agisoft Metashape	Autodesk Revit	Enscape/Unity Reflect
2	360-Degree Specialty Camera - Insta 360 Pro 2	Point Cloud - Pix4D Mapper Agisoft Metashape	Autodesk Revit	Enscape/Unity Reflect
3	Faro M70 Laser Scanner	Point Cloud	Faro Scene	Faro Scene
4	360-Degree Commercial Camera - Insta 360 ONE X2	3D Stitched Panoramas	3D Vista/ Matterport Capture	3D Vista/ Matterport
5	360-Degree Specialty Camera - Insta 360 Pro 2	3D Stitched Panoramas	3D Vista/ Matterport Capture	3D Vista/ Matterport

Alternative 1 and 2

As referred in Table 3. Alternative 1 and 2 consisted in utilizing a 360-degree camera to generate a dense point cloud file based on the 3D panoramas taken with these devices. In order to do this, we tested out 2 different software programs that have the capability to process panoramas into a dense point cloud file: Agisoft Metashape and Pix4D Mapper. Multiple images were taken of both an indoor environment and an indoor room under construction. After processing the spherical panoramas of these spaces into a point cloud file and generating the 3D model of the space, we subjectively determined that the quality produced by both software products would not be enough to generate an IVE for our HBI testing purpose, given the criteria of Immersion and Presence specified earlier. In addition, IVE software generators such as Enscape and Unity Reflect could not process/render point cloud files into an IVE given that they are object-based software. It is important to mention that 360-degree cameras in the Commercial and Specialty categories were utilized in both Alternative 1 and 2, respectively, with no meaningful differences in the quality of the product. As it can be appreciated in Figure 3 below, some features of the building such as walls and ceilings were not very well defined, and therefore, these 2 alternatives failed for the purpose of our research.

Table 4. 3D Model of Indoor Environment generated with 360 Image Based Technology

Alternative 3

As referred in Table 3, this alternative consisted in utilizing a Faro M70 laser scanner as a reality capturing device of the same spaces. Laser scanners are the reality capturing device of choice when accurately capturing the geometry and dimensions of the space is a priority. In contrast to 360-degree cameras, laser scanners generate point cloud files automatically, without the need for extra processing software. The generated model was then experienced utilizing the built-in VR capability of the Faro Scene software. After trying different scanning modalities (higher density point cloud and quality/resolution) we subjectively evaluated that the quality of the IVEs generated with the Faro Scene software would not be enough to satisfy our initial objective of generating a realistic IVE to enable human building interaction elements. The main limitation regarding this workflow was related to scanning time constraints. In order to attempt to use the highest quality scan possible, each scan would take around 3 hours to complete. Given that we needed 6+ scans for the space in consideration, the utilization of a laser scanner for the purpose of our research was considered to be redundant.

Alternative 4 and 5

These alternatives consisted in utilizing 360-degree cameras as the reality capturing device of the built environment. The obtained spherical panoramas are automatically processed by the software into a 3D model with IVE visualization capabilities. Depending on the software that it is utilized (Matterport or 3D Vista), some interactive information can be integrated to the Immersive Virtual Environment. For instance, 3D Vista allows the integration of graphical information, video, and audio files to increase the quality and user experience within the IVE.

Due to these experiences and limitations with the first 3 alternatives presented in Table 3, the scope and objective of research were redirected and narrowed down to just emphasize an evaluation of 360-degree image based IVEs (Alternatives 4 and 5) compared to common practice of graphical IVEs (BIM based).

2. Research Objective and Questions

The primary objective of this research is to determine whether IVEs generated with 360-degree technology are an adequate representation of the built environment regarding Human Building Interaction, and how these IVEs are compared to commonly used graphical IVEs generated with Building Information Modeling (BIM) authoring tools. In order to achieve the objectives of this research, a user experiment study was adopted and a preliminary data collection was performed in an academic setting to explore and test out with different human subjects the Human-Building Interaction (HBI) in such IVEs. The specific research questions that we seek to answer with this study are to investigate the following:

- RQ1: Are the 360 Image Based IVEs an adequate representation of the built environment from the end user's perspective regarding HBI?
- RQ2: How are 360 Image Based IVEs compared with Graphical IVEs for the study of human building interactions considering human performance?

3. Related Work

As mentioned at the beginning of this paper, there have been various applications of 360-degree cameras and immersive virtual environments for different purposes. For instance, regarding the use of 360-degree camera for photogrammetry purposes only, a very common application has been in cultural heritage and preservation. Barazzetti et al. explored the use of low-cost 360-cameras to generate point clouds of a basilica in Italy and compared them to a point-cloud generated with a regular DSLR camera [33]. Similarly, Murtiyoso et. al. utilized a DSLR camera, a drone, a 360-degree camera and a laser scanner to generate a dense point-cloud of the exterior of a Buddhist temple in Indonesia [34].

Another important application of 360-degree imagery and IVEs has been in the real estate virtual tour field. This area in particular has grown in popularity and demand due to the ongoing COVID-19 pandemic that started in 2020. The need for people to explore different spaces without being physically present made virtual tours a feasible alternative and therefore more attractive to researchers. Sulaiman et al. explored the use of a virtual tour software like Matterport to evaluate its features compared to other conventional methods based on 4 different criteria: accessibility, visual capture, details information and visual experience. Their conclusion regarding this software is that it provides users with spatial cues that strengthen the sense of presence within the generated virtual environment [48]. Similarly, IVE virtual tours have also been generated to gauge prospective students' reaction towards higher education facilities. For instance, IVEs of 2 Indonesian universities were recently developed for this purpose. Both studies revealed that these IVEs generated a positive response towards the campuses and attracted prospective students to learn more about these institutions [44, 49].

3.1 Virtual Reality and Human-Building Interaction

Human-Building Interaction in IVEs has been a topic of discussion for several years now. There have been many different research studies that have sought to determine if a virtual environment could be a high-fidelity representation of a physical environment when enabling HBI elements. The most common software applications to develop and visualize these IVEs have been utilizing Revit and Unity 3D respectively (Graphical IVEs), due to its great capacity to add interactive elements within the environment. There have been studies in which participants are asked to complete certain tasks in the IVE to assess the HBI in different indoor spaces. For instance: performing office related tasks like reading passages and counting books from a bookshelf [1], adjusting the thermostat/fan temperature [27], changing the lighting conditions for energy saving purposes [20], wayfinding and navigation for occupant behavior assessment [4], building emergency evacuation [50, 51], and evaluating human experience in the built environment utilizing body sensor networks [52]. The conclusion of these different user studies has concurred that Graphical IVEs can be an adequate representation of a physical interior environment regarding given that the proper interactive conditions are present [1, 4, 20, 27].

3.2 360-Degree Imagery and Virtual Reality

There have been different user studies that have explored the utilization of 360-degree imagery in virtual environments, with the purpose of assessing and comparing them to a physical environment. For example, Higuera-Trujillo et al carried out a user study with three different simulations of the built environment (a supermarket aisle): regular photographs, 360-degree images and an immersive virtual environment. The psychological (questionnaire response) and physiological (electrodermal activity) responses of the participants were measured and analyzed to determine which of these 3 representations was the most valid when compared to those of the physical environment [53]. However, in the 360-degree image-based environments, participants were only able to look around the environment without the ability to navigate or interact freely within the environment.

An early approach to 360-degree imagery and graphical IVEs integration has also been explored by researchers. Walmsley and Kersten developed an immersive VR application of a cathedral in Germany, by integrating data acquired with a laser scanner and a DSLR camera. This data was then transferred to AutoCAD for 3D modelling, Substance Painter for texture mapping, and then to the Unreal game engine to generate such VR application. An HTC Vive Pro (HMD) was utilized for visualization of this particular application, in which 360-degree panoramas were integrated through visual cues within the IVE [54].

Moreover, there have been user studies focused on the AEC industry pertaining the utilization of 360-degree imagery and virtual environments. For example, Kim et al was the pioneer in integrating 360-degree technology with construction site field trips. In this study, participants observed sequential 360-degree images of the construction process of a concrete foundation wall. The objective of this study was to determine whether these 360-degree images of the construction site could generate an environment that was real enough that could actually replace the need of a site visit to understand the construction process [55]. Similarly, Eiris et al created a virtual environment focused on virtual construction site visits called iVisit. The objective of this VE is to provide construction management education and training without the inherent obstacles and dangers that physical construction sites involve [56]. iVisit was developed utilizing 360-degree images and augmented utilizing the Unity 3D engine. However, this virtual environment was not an IVE, as it is a desktop-based computer environment, where users utilized a 3D virtual human (3rd person point of view) to navigate it. Two experiments were performed utilizing iVisit. The first one was a pilot study focused on measuring the usability, presence, and student performance on the virtual environment, in order to generate user feedback to utilize it in larger scale studies [56]. The second experiment benefitted from this feedback and utilized the iVisit platform to assess this virtual environment regarding collaborative problem-solving between users [57].

The gap in knowledge that our research seeks to fill is to investigate HBI in immersive virtual environments generated by utilizing 360-degree cameras and compare it to that of graphical immersive virtual environments, which have already been benchmarked as an adequate representation of the built environment. This will be achieved through a preliminary study with human subjects that are students in the Virginia Tech campus, ranging from undergraduate to graduate students enrolled to the university. This specific process will be explained in the following section.

4. Research Methodology

4.1 Model and Apparatus

Two different IVEs were created for the purpose of our user study: a 360-degree image based IVE, and a Graphical BIM modeled IVE. The 360-degree camera that was utilized to develop the first IVE was the Insta360 One X2. The second IVE was created by utilizing the original floor plan dimensions and modeled in Autodesk Revit. From Revit, the model was rendered and transferred to Enscape, which is a plug-in platform that has the capability of generating high-quality renderings for Virtual Reality visualization. Another reason for utilizing Enscape as the IVE Visualization platform is because it has a smooth and straightforward workflow in generating the IVE, as it is a platform that downloads as a Revit plug-in, so any changes made to the BIM model are automatically reflected in the IVE. Both IVEs were visualized utilizing an Oculus Quest 2 HMD, which provides an LCD panel with a 1832 x 1920 display resolution. The Quest 2 includes two controllers (one for each hand) with an integrated tracking ring. The computer that was utilized to run the IVEs along the Oculus Quest 2 was a Silverdraft Demon workstation , with an NVIDIA GeForce RTX 2080 Ti graphics card driver.

4.2 Experiment Design

The generated IVEs are a representation of a 1400 sq. ft. two-room computer laboratory in Patton Hall, at the Virginia Tech campus in Blacksburg, Virginia. As explained in the last section, there were 2 different IVEs generated for the purpose of our study: a 360-degree virtual tour in Matterport, which is a 360-based IVE, and a graphical IVE generated in Revit and Enscape. With these 2 different environments, participants had to complete a couple of simple tasks that will serve us to determine whether the use of 360-degree cameras is feasible enough to generate IVEs that can be validated as a high-fidelity representation of the built environment regarding human-building interaction. These tasks will be explained further in the following sections. The two IVEs generation workflow is Figure 3 below:

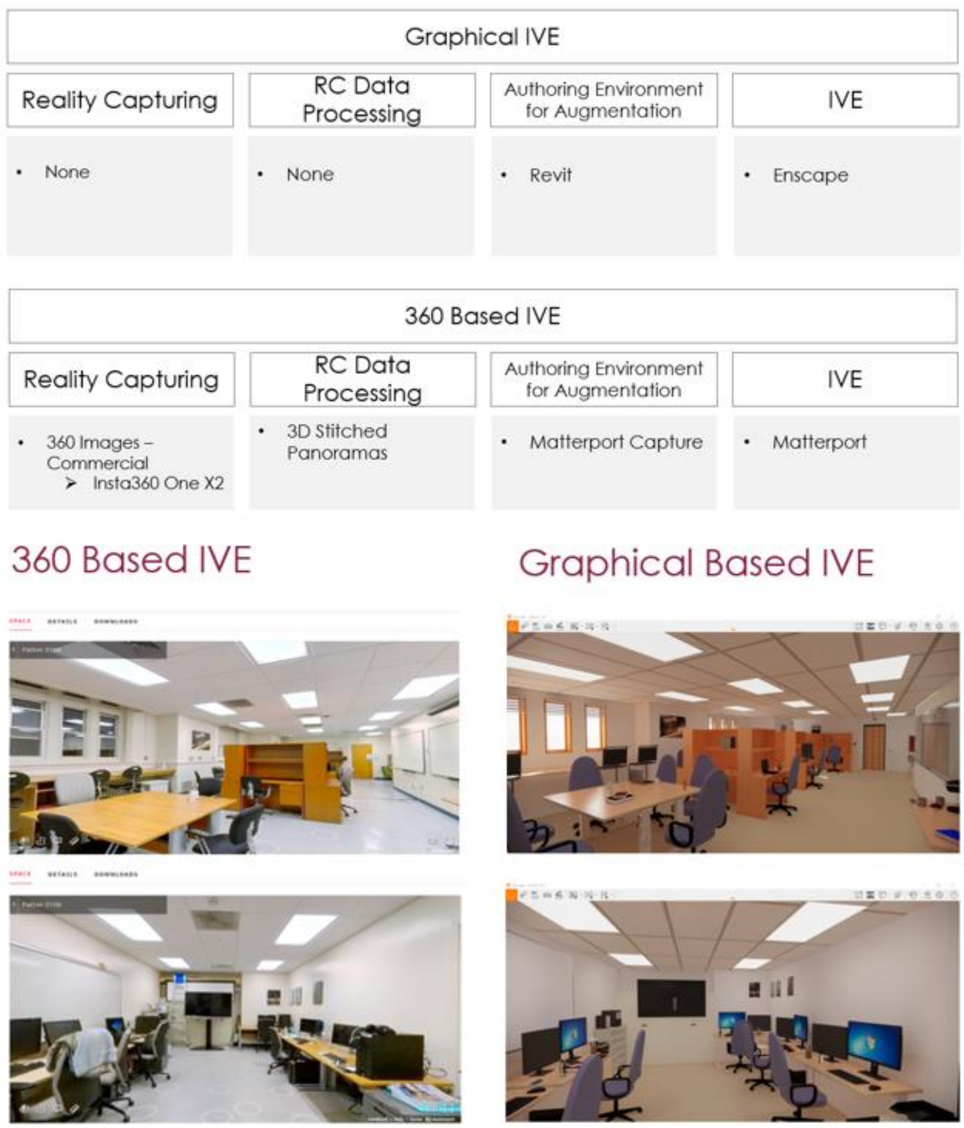

Figure 3. IVE Generation Workflow

These IVEs were explored by participants in two different lighting conditions: dark and bright. The reason behind testing out both IVEs in the two different lighting conditions follows the findings of several other research studies that have concluded that lighting conditions are a defining factor that affect end-user performance and interaction with the built environment when humans are involved in task completion [1, 20, 52, 58-61]. Therefore, the purpose of measuring user performance and immersion/presence in these two lighting conditions is to determine whether a 360-degree based IVE can be an adequate representation of the built environment, just like a normal graphical IVE has already been benchmarked in other user studies ran by Heydarian et al [1, 5, 58] , in which they compared a graphical generated IVE to a physical environment in the same two different lighting conditions. The objective of our study is to accomplish the same comparison by adopting the methodology of these studies, but with the two aforementioned IVEs (360 vs Graphical). The participants will perform 2 different tasks in each environment. The hypothesis is explained in the Figure 4 adapted from Heydarian et al [1, 5]. The two hypotheses that will be tested are the following:

(1) There will be statistically significant differences between lighting conditions across both IVEs

(2) There will not be any statistically significant differences in the changes in performance across the IVEs

Regarding the first hypothesis, Heydarian et al argued that given the different lighting conditions, there would be significant differences in performance between these lighting configurations in both IVEs. When it comes to the 2nd hypothesis, they sought to determine if these changes in performance are statistically similar ($\Delta_1 = \Delta_2$). If this is the case, the argument that the IVEs are an adequate representation of each other and therefore, the built environment, can be supported regardless of the difference in performance between lighting conditions.

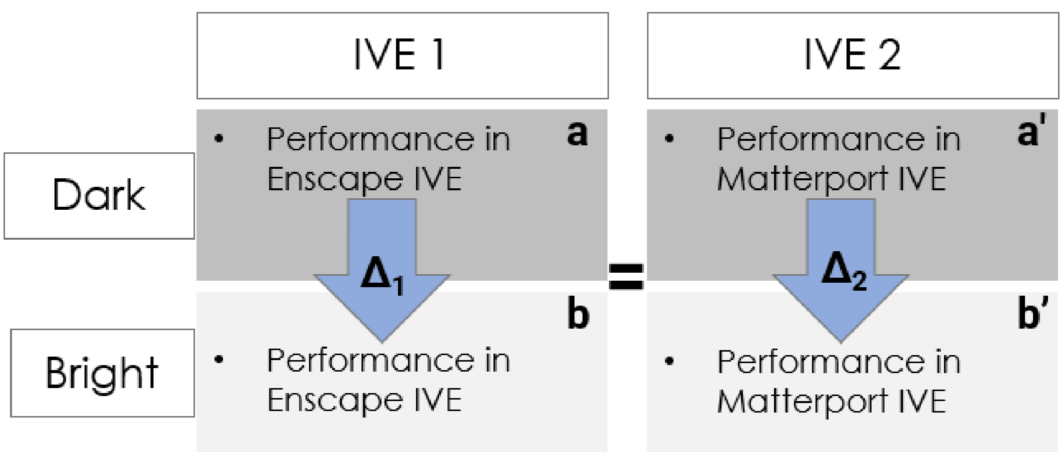

Figure 4. Experiment Hypothesis adapted from [1]

5. Experiment Details

5.1 Recruitment

This research user study was available for any interested undergraduate/graduate students, and faculty/staff of Virginia Tech. This study was approved by the Internal Research Board (IRB Protocol #20-787). The study participants were compensated with a $10 gift card as a retribution for their time (60-120 min.). The number of participants in this preliminary study were a total of 13 (9 male and 4 female) given the time constraints of the experiment. All the participants were engineering students, with mostly civil (10), industrial (2), and mechanical (1) engineering majors at Virginia Tech. Regarding demographics, there were 11 international students (English as their secondary language) and 2 American (English as their first language).

5.2 Experimental Procedure

As it has been previously mentioned, the participants completed the same two different set of tasks in the 2 different IVEs, with 2 different lighting conditions. Therefore , totaling 4 different IVE interactions as explained in Figure 4 above. Adopted from the task settings in previous studies [1, 4, 5, 62], tasks in this study involved (1) reading, (2) navigation and object identification/finding. Also consistent with previous benchmark studies [1, 5] the metrics that will be evaluated in order to answer our research questions will be user performance and level of immersion and presence reported in such IVEs. Before starting the experiment, participants read and signed the IRB-approved consent form pertaining to this study (IRB 20-787). Prior to completing the tasks in each environment, participants went through a general overview of what the experiment would consist of, and a short 5-minute training in a sample IVE for each environment configuration (360 Image Based and Graphical), in order to understand how to interact and navigate within both IVEs, and to become familiar with the interface of the IVE and the controllers. Once participants felt comfortable enough with navigating within the IVE and utilizing the hardware, participants were asked to remove the HMD and to report whether they felt any motion-sickness or any kind of discomfort prior to starting the experiment. If this was the case, participants were thanked for their intention to collaborate with the study and dismissed from the experiment to prevent any further health issues. In this pilot study, only 1 out of the 13 total participants experienced motion sickness and discomfort after such training, so this participant was thanked and dismissed from the experiment.

For every IVE interaction, the first task involved reading a short passage (150-240 words) that was displayed in each IVE, on the virtual TV screen present at one of the rooms, as it can be appreciated in the experiment setup shown in Figure 5 below. These passages were different in each of the 4 IVE interactions, and they were obtained from AceReader [63], which is a website focused on reading speed and comprehension. This website ensures that the level of difficulty stayed consistent across the 4 different options that were selected for the experiment. Participants were informed that the time for the reading task would be recorded, and there would be a short reading comprehension questionnaire afterwards. Therefore, reading at a good pace while understanding the content was highly encouraged. It is important to mention that the order of the IVEs in which participants started, whether it was the 360 Image Based or the Graphical IVE, was alternated with every participant to eliminate or decrease any chance of order effects. When the participants indicated that they had finished the passage, the time was stopped, recorded, and the participants were instructed to take off the Oculus HMD, and head towards the laptop computer to answer the reading comprehension questionnaire, which ranged from 3-4 questions, also obtained from the AceReader website. Once participants finished, they were reminded of what the second task would consist of.

The second task involved virtually navigating around the two laboratory rooms and identifying the total number of objects that were randomly distributed around the space. These objects were not hidden, but they were spread out enough around the 2 rooms to provide a meaningful level of difficulty. The object that participants had to look for was specified at the beginning of every IVE interaction, and they were different for every IVE configuration. The selection of objects that participants had to find were coffee mugs, plastic bottles, pencil containers and water cups. All these items were selected because they are considered to be items that are common in an academic environment, like the one where research participants were navigating in and interacting with. At the beginning of each object finding task, participants were informed that they had a limited time window to complete this task (1 minute), and at the end of this time they had to report as many objects as they were able to find in the IVE within that time window.

Figure 5. Experiment Setup (top and bottom left – reading and object finding task in 360 IVE, top and bottom right – reading and object finding task in Graphical IVE)

After participants either completed the second task or they ran out of time, they had to complete 2 different questionnaires evaluating their overall experience with the IVE in question. The first one was related to feeling of presence and immersion in the IVE, and the second one was related their task load perception while performing such tasks. The first questionnaire was comprised of 18 questions, in a seven-point Likert scale. The sample questions and the pertaining results from the participants are shown in Table 4 below. The objective of this questionnaire was to assess their level of presence and immersion, and it contained questions adapted from Witmer and Singer's questionnaire [64], which has been highly validated in the academic community when it comes to measuring presence in immersive virtual environments. The questions that were left out from such questionnaire were related to the Auditory and Haptic Stimulation subscales, given that our IVEs do not provide neither auditory nor haptic stimulation to the participants. As previously mentioned, along with user performance, presence and immersion are one of the benchmarked metrics that we will measure to answer our research questions.

Similar to other user studies involving task completion in virtual environments [65-68], and given that our selected tasks are cognitive in nature, the second questionnaire that participants had to complete after completing the tasks was the NASA Task Load Index (TLX) questionnaire. This questionnaire is comprised of 6 questions that asses the perceived workload for each subject after the completion of these tasks in each of the presented IVEs. These subjects are regarding to physical, mental and temporal demand, performance, effort and frustration. With this questionnaire, we intend to determine whether there is any relationship between the user performance and their reported level of presence and immersion with the reported subjective workload. The sample questions and the pertaining results from the participants are shown in Table 6 below. Lastly, once the participants went through all the 4 different IVE configurations and completed the questionnaires for the 2 types of IVEs, participants had to respond to 3 questions that compared their overall experience when navigating and interacting with Matterport and Enscape as IVE visualization platforms. The sample questions and the pertaining results from the participants are shown in Table 5 below.

6. Data Analysis and Results

A power analysis was performed in order to determine the statistical significance of the results of our study. The results of such power analysis showed that 64 participants would be required to have at least the minimum required power of 0.8 and effect size of 0.5, as shown in Figure 6 below. Given our sample size (n=12), the data analysis performed, and results obtained cannot be used to generalize any findings, but they will serve as a preliminary study to indicate trends and to serve as guidance in future research studies. The results of our preliminary study are divided into 2 categories, (1) Experiment Performance results and (2) the Presence, Immersion and Workload Questionnaire results.

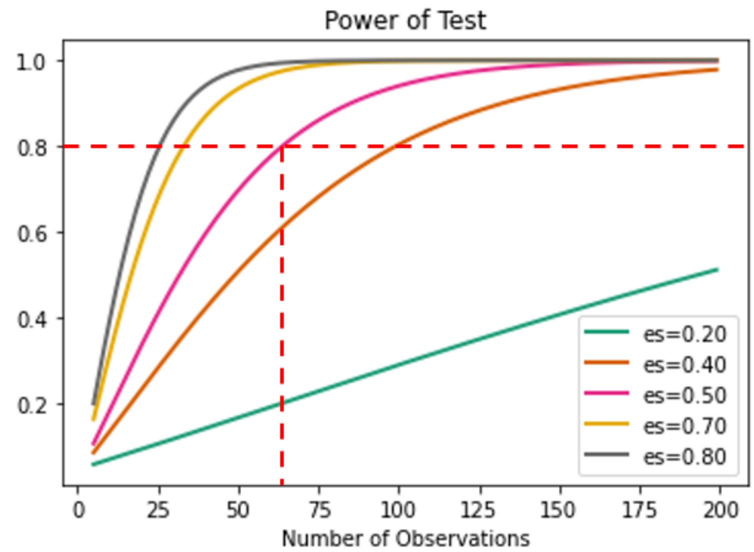

Figure 6. Power Analysis Results

6.1 Experiment Performance

The initial hypothesis of the experiment stated that there would be statistically significant differences in user performance between lighting conditions across both IVEs. In order to test such hypothesis, the participant performance results between dark and bright conditions were analyzed by running a paired sample *t*-test for each observed category: reading speed (words per minute), reading comprehension (ratio of correct questions to total questions) and object identification (ratio of identified objects to total number of objects present). To determine whether a difference in performance is statistically significant, the *p*-value of a *t*-test has to be lower than 0.05. For the reading speed category, the *p*-values for the dark and bright Graphical and 360 IVEs are 0.155 and 0.137 respectively; both of which are greater than .05. Therefore, there was no statistically significant difference in performance in either for such category. For the reading comprehension category, the *p*-values for the dark and bright Graphical and 360 IVEs are 0.169 and 0.324 respectively; both of which are greater than .05. Again, there was no statistically significant difference in performance in either. Lastly, for the object identification category, the *p*-value for the dark and bright Graphical and 360 IVEs are 0.049 and 0.194 respectively. The *p*-value for the Graphical IVE in this category was less than .05, and therefore, a statistically significant difference in performance was present in this IVE. Based on these results, the hypothesis statement that there would be a significant statistical difference in user performance between all lighting conditions could not be confirmed.

The initial hypothesis also intended to identify whether there is a significant difference in the changes in performances between both IVEs. In other words, whether the results of Δ_1 and Δ_2 are significantly different. As mentioned before, the delta (Δ) represents the changes in performance between dark and bright condition. After analyzing the participants' results, there were no statistically significant differences found in any of the 3 experiment categories. For the reading speed category, the *p*-value obtained was 0.298. For the reading speed comprehension, the *p*-value obtained was 0.314. For the object identification category, the *p*-value obtained was 0.059. Therefore, the statement that the change in the performance in both IVEs is similar was confirmed ($\Delta_1 = \Delta_2$). The summary of the experiment performance results is presented in Table 5 below.

Table 5. Experiment Performance Results

	$\Delta_1 = \Delta_2$	**Dark and Bright Graphical**	**Dark and Bright 360 Image Based**
Reading Speed			
t-Test	-0.547	-1.066	-1.150
p-Value	0.298	0.155	0.137
Reading Comprehension			
t-Test	0.498	-1.000	-0.469
p-Value	0.314	0.169	0.324
Object Identification			
t-Test	-1.699	1.812	-0.900
p-Value	0.059	0.049	0.194

The mean value for the participants results were also calculated for each category. When looking at these results more closely, it can be identified that the experiment participants were able to perform better in the dark environment configuration for both IVEs in the task related to reading, both in speed and comprehension. Similarly, participants performed better in the 360 Image Based IVE in the reading related task (reading speed and comprehension). Their mean reading speed was 187 words per minute compared to 149 in the Graphical IVE for the dark environment configuration, and 173 words per minute compared to 141 for the bright environment configuration. The mean reading comprehension ratio of correct questions was also higher: 0.78 compared to 0.77 in the Graphical IVE in the dark environment configuration, and 0.75 compared to 0.69 for the bright environment configuration. In contrast, participants performed better in the Graphical IVE in the object identification task. The mean ratio of identified objects to the total number of objects was 0.79 compared to 0.75 in the 360 Image Based IVE for the dark environment configuration, and 0.87 compared to 0.67 for the bright environment configuration. The reason for this better performance in the Graphical IVE in tasks related to navigating and object finding could be explained since the Graphical IVE offered the possibility of navigating around environment more freely, and the users are not limited to the predetermined locations of the “hotspots” where the 360-degree panoramas where taken, as it is the case with the 360 Image Based IVE. The mean value performance results are summarized in Figure 7 below:

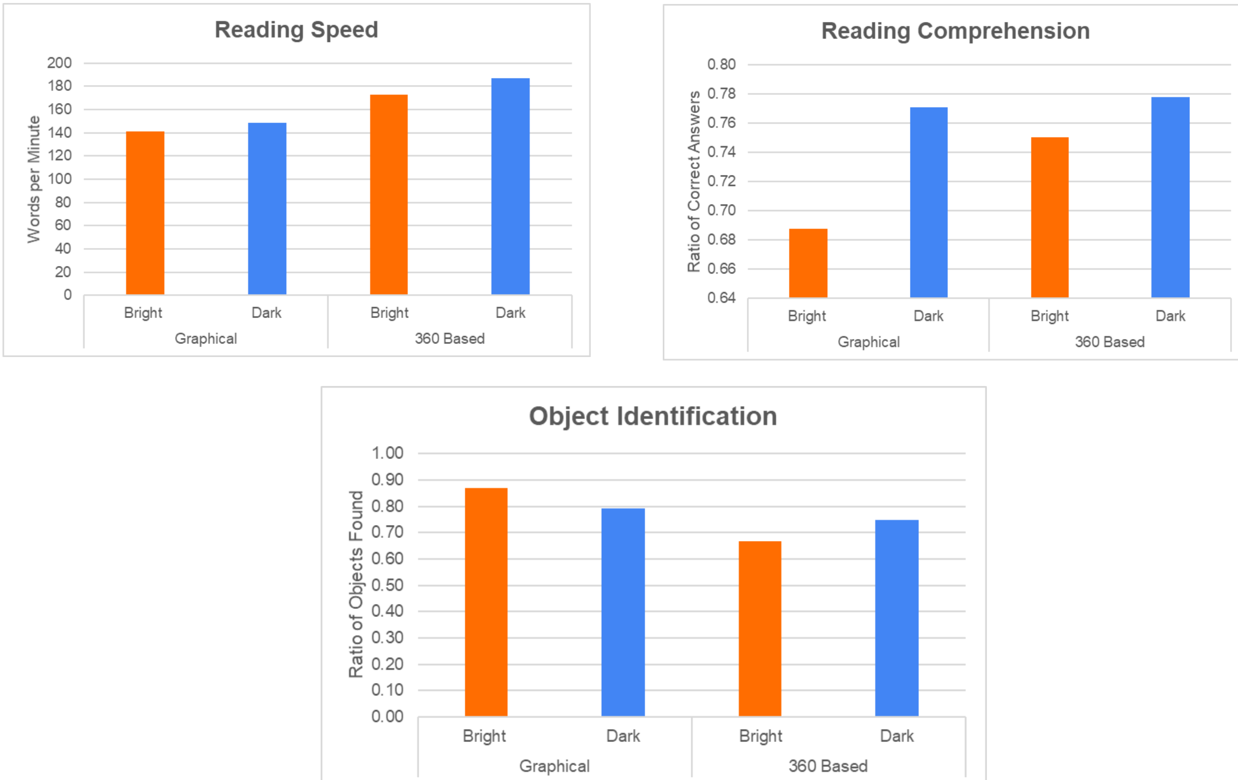

Figure 7. Performance Results for each IVE Configuration

6.2 Presence, Immersion and Workload Questionnaire

As previously stated, one of our research objectives is to determine whether the created environments by using 360-degree camera technologies are perceived to be immersive and realistic from the end user's perspective as a metric to respond to our research questions . For this reason, the mean and standard deviation were calculated for the responses of each of the participants' questionnaires, and the results for both IVEs were analyzed. The 360 Image Based IVE outperformed the Graphical IVE in every question of the presence and immersion questionnaire, with the exception of Q1 and Q16, in which the calculated means were the same. Overall, the 360 Image Based IVE received a mean total score of 85.42 out of 126, compared to 83.08 for the Graphical IVE. In order to determine whether there was a significant difference in the responses for each IVE, a paired sample *t*-test was performed for every question score. Again, the *p*-value for a t-test has to be less than 0.05 for a for a difference in the responses to be considered statistically significant. Even though there was a higher score associated to the participant responses for the 360 Image Based IVE, no statistically significant difference could be found in any of the questions. Therefore, it could be concluded that the participant's feeling of presence and immersion was similar for both IVEs. The results of the participant scores for every question is summarized in Table 6 , and their overall mean score for each is represented in Figure 8 below.

Table 6. Presence and Immersion Questionnaire Results

Presence and Immersion – Sample Questions	Mean		Standard Deviation		Paired *t*-test (*p*-value)
	Graphic	**360 Image Based**	**Graphic**	**360 Image Based**	
1. How much were you able to control events?	5.33	5.33	1.50	1.67	1.000
2. How responsive was the environment to actions that you initiated (or performed)?	5.67	5.83	1.37	.0.83	0.504
3. How natural did your interactions with the environment seem?	4.58	4.67	1.62	1.23	0.881
4. How completely were all of your senses engaged?	5.00	5.08	1.28	1.24	0.754
5. How much did the visual aspects of the environment involve you?	4.75	5.42	1.48	1.51	0.255
6. How natural was the mechanism which controlled movement through the environment?	4.58	4.33	1.56	1.56	0.623
7. How aware were you of events occurring in the real world around you?	3.17	3.25	1.59	1.76	0.795
8. How completely were you able to actively survey or search the environment using vision?	5.17	5.58	1.34	0.67	0.339
9. How compelling was your sense of moving around inside the virtual environment?	4.58	5.08	1.73	1.62	0.491
10. How closely were you able to examine objects?	5.25	5.33	1.54	1.61	0.874
11. How well could you examine objects from multiple viewpoints?	5.33	5.50	1.78	1.00	0.787
12. To what degree did you feel confused or disoriented at the beginning of breaks or at the end of the experimental session?	2.75	2.58	1.36	1.56	0.723
13. How involved were you in the virtual environment experience?	5.17	5.50	1.19	1.09	0.220
14. How much delay did you experience between your actions and expected outcomes?	3.08	2.75	1.56	1.54	0.266
15. How quickly did you adjust to the virtual environment experience?	5.08	5.42	1.38	1.08	0.305
16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	5.58	5.58	1.44	1.16	1.000

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?	3.33	3.83	1.67	1.95	0.477
18. Were you involved in the experimental task to the extent that you lost track of time?	4.67	4.33	1.87	2.19	0.339
TOTAL	83.08	85.42			

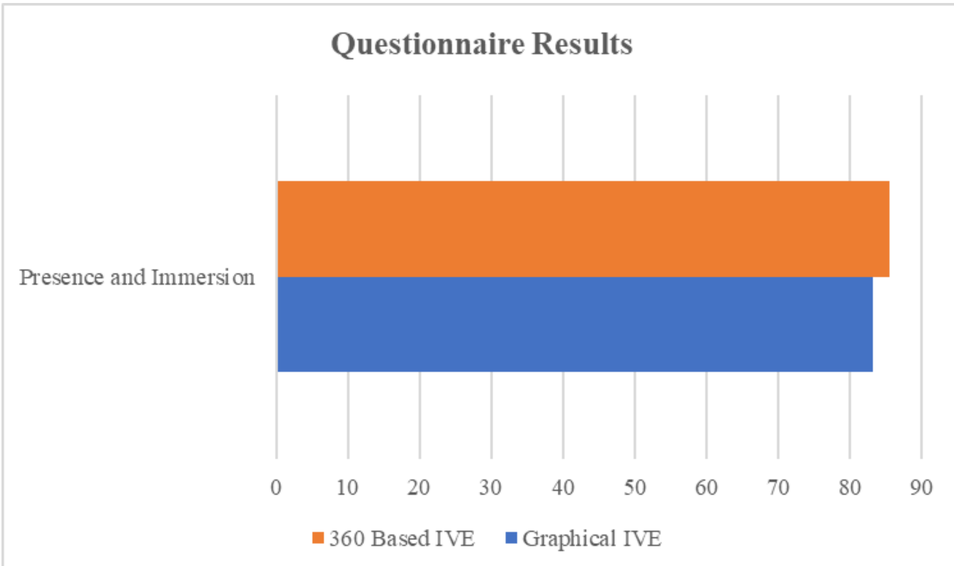

Figure 8. Presence and Immersion Questionnaire Results

Another objective of the questionnaire was to compare whether these environments were similar enough between each other so that the results of this pilot study could be validated, and potentially improved in further research studies. The participants were asked to compare how similar these IVEs were to each other in the two different lighting conditions. Participants responded that in average, the bright environment configuration was more similar than the dark environment configuration, with a 4.33 mean score out of 7, compared to a 3.67 for the dark configuration. Moreover, participants were also asked to determine which IVE felt closer to reality after interacting and navigating in each one of them. Overall, 8 participants (67%) responded that the Matterport IVE felt more real compared to the real physical environment, compared to only 4 participants that picked the Enscape IVE (33%). The results of this comparison in particular are in line with the results of the presence and immersion questionnaire. The results of the participant responses for the comparison questions are summarized in Figure 9 and Table 7 below.

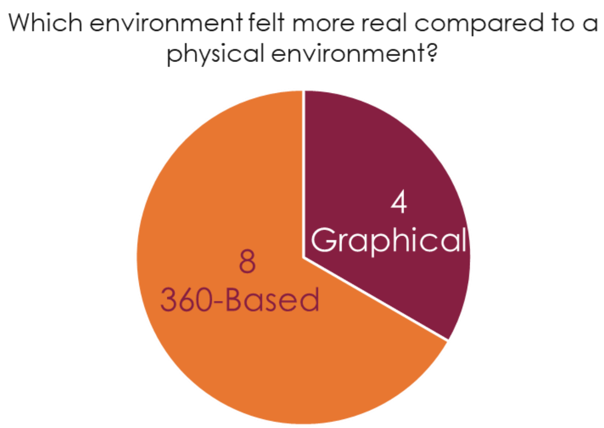

Figure 9. IVE Comparison Results

Table 7. IVE Comparison Questionnaire Results

IVE Comparison - Sample Questions	Mean	Standard Deviation
Comparing the dark room in the 360 Image Based IVE and the dark room in the Graphical IVE, how similar did you feel these two environments were?	3.67	1.37
Comparing the bright room in the 360 Image Based IVE and the bright room in the Graphical IVE, how similar did you feel these two environments were?	4.33	1.37

Lastly, the workload questionnaire (NASA TLX) was also utilized as an additional mean of validation and comparison across the IVEs. As previously mentioned, this questionnaire evaluates different aspects (physical, mental and temporal demand, performance, effort, and frustration) of the subject's responses regarding the perceived workload associated with completing the tasks in each IVE. The mean and standard deviation were calculated for every question associated with each subject, and a paired sample t-test was also performed to determine whether there are any statistically significant differences regarding participant's workload. Ultimately, although no statistically significant differences were found when comparing IVEs, participants reported a higher mean score of 23.92 out of 42 for the Graphical IVE, compared to a 22.34 for the 360 Image Based IVE, suggesting that the perceived workload for the Graphical IVE was higher. In addition, this can be reflected in Q5 where participants where asked how hard they had to work to accomplish their level of performance. Although not statistically significant (p-value =.108 > 0.05), participants did report a higher workload score for the Graphical IVE (4.5 out of 7), compared to the 360 Image Based IVE (3.75 out of 7). These results could potentially also be associated with the perceived feelings of immersion and presence obtained in the questionnaire, and how realistic the IVEs were perceived to be by the participants, which will be discussed further in the next section. The results of the participant responses for NASA TLX workload questionnaire are summarized in Table 8, and their overall mean score for each is represented in Figure 8 below.

Table 8. NASA TLX Workload Questionnaire Results

NASA TLX - Sample Questions	Mean		Standard Deviation		Paired t-test
	Graphical	360 Image Based	Graphical	360 Image Based	
How mentally demanding was the task?	3.75	3.92	1.14	1.16	0.504
How physically demanding was the task?	3.33	2.75	1.56	1.42	0.294
How hurried or rushed was the pace of the task?	4.42	4.42	1.51	1.78	1.000
How successful were you in accomplishing what you were asked to do?	5.17	5.25	1.27	0.97	0.857
How hard did you have to work to accomplish your level of performance?	4.50	3.75	1.17	1.29	0.108
How insecure, discouraged, irritated, stressed, and annoyed were you?	2.75	2.25	1.54	1.48	0.324

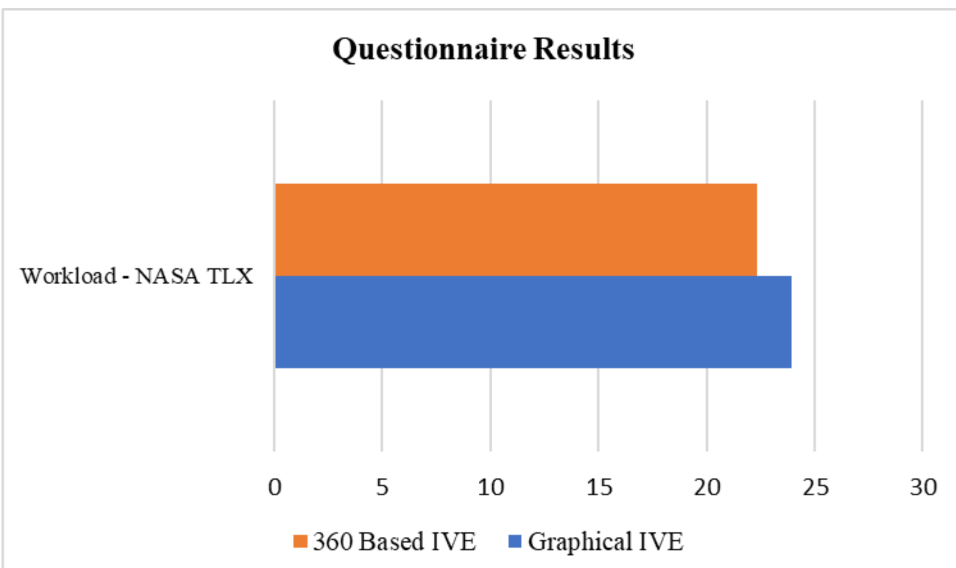

Figure 10. Workload Questionnaire Results

7. Discussion

Although the number of participants (n=12) were not sufficient to test the experiment's hypotheses, we have evaluated the findings to assess potential validity of those hypotheses to inform future research in statistical evaluation. The results of our pilot user study reflected that the participants in the experiment did experience a strong feeling of immersion and presence in the 360 Image Based IVE. Moreover, although not statistically significant, the results of our preliminary study also showed a stronger feeling of immersion and presence in the 360 Image Based IVE compared to that of the Graphical IVE modeled with BIM authoring tools like Revit and Enscape. This result follows the findings of other user studies. For instance, the study performed by Trujillo et al also concluded that participants reported a higher psychological response related to presence in the 360-degree panorama based environment in comparison to traditional virtual reality and regular photographs [53]. However, the participants in such study did not have the ability to move around the space in the 360-degree based environment. In addition, the majority of the participants selected the 360 Image Based IVE as the IVE that resembles the closest to the physical environment. Although this was already expected given the fact that a 360 Image Based IVE is made from pictures of the actual environment, our preliminary study sought to confirm whether these results would be consistent when participants had human-building interaction elements such as task completion and navigation within the IVE.

Regarding user performance in the two different IVEs, the findings of our pilot study could not test the first hypothesis that there would be statistically significant differences between lighting conditions across both IVEs. While this could be related to the inherent characteristics of the virtual environments that were developed, some other factors such as the quality of the IVEs could have also affected the results. This could potentially be associated with the lower scores reported in Table 5 regarding the similarity between the IVEs and their different lighting configurations. Therefore, ensuring a stronger similarity in the lighting conditions should be explored in further detail in following research studies. However, considering that the data shows low likelihood of significant differences between different lighting conditions, the difference in changes in performance (Δ_1 and Δ_2) were proved to be similar, and therefore the hypothesis that both the 360 Image Based IVE and the Graphical IVE are similar representations of the built environment based on the user performance could potentially be supported. These results follow the findings of the research that the methodology for our user study was based on [1, 5].

Overall, participants also reported high scores regarding user functionalities in both environments such as visual surveying of the space, perception of movement and visual engagement with the different features of the environment. Again, these scores were higher for the 360 Image Based IVE, but statistical significance could not be evaluated. However, these higher scores could be associated with the results of the NASA TLX workload score; in which users found more physically and temporally demanding to complete the tasks in the Graphical IVE compared to the 360 Image Based IVE. However, regarding the object finding task, the results of our experiment showed a reduced user performance in the 360 Image based IVEs, contrary to our general expectation of them being closer to real-world environment. This should be explored in future research studies, as it will be explained in the next section.

8. Limitations and Future Research

A clear limitation of this research study is the sample size of the experiment (n=12). The sample size should be increased based on the findings of the power analysis to be able to draw conclusions on the significance of differences between the user experiences in these two environments.. In addition, consistent with previous user studies, the parameters that were measured in this research study were presence and immersion, workload and user performance regarding certain tasks that are considered to be cognitive in nature, such as reading and object finding. However, further exploration of different tasks in different built environment settings could be explored to generalize any findings.

Moreover, participants were not able to interact with any objects in either IVE given the technical limitations of both the Graphical and the 360 Image Based IVEs. Future research could look more into enabling participant interaction with surrounding objects in the IVEs. Since this is not possible in the software utilized for both IVEs (Matterport and Enscape), this would entail utilizing a different IVE visualization platform that are more object interactive such as 3D Vista for 360-degree based IVEs, and the Unity 3D game engine for the Graphical IVEs. Additionally, the integration of auditory or haptic interactions in the IVEs could be explored with the hopes of generating a stronger feeling of realism to the users.

Another limitation of this research study is the utilization of a 360-degree camera in the Commercial category. As previously explained, cameras in this category offer lower resolution compared to cameras in the Specialty category. Therefore, an area of opportunity for future research could integrate the utilization of Specialty 360-degree camera such as the Matterport Pro2 3D or the Ricoh Theta Z1, to name a couple. The benefits of utilizing these higher scale sensors could be a potential increase in the feeling of presence and immersion in the 360-degree based IVEs, hence, a better overall user experience within the IVE.

9. Conclusions

This research presents a workflow for the generation of an Immersive Virtual Environment (IVE), and a framework with different alternatives to generate both a 360-degree technology based, and a Building Information Modeling (BIM) based IVE. We hypothesized that the 360 Image-based IVEs could potentially improve human experiences and performance compared to traditional IVEs although they provide less interactivity. Two of these specific alternatives were tested and compared by the means of a pilot user study in order to evaluate the human-building interaction (HBI) on the 360-degree based IVE compared to a BIM based Graphical IVE. The main objective of this research was to determine whether 360-degree based IVEs could also be an adequate representation of the built environment to assess building occupant interaction, with applications in the AEC industry in both the design and post-construction stages. Adopting previously tested methods in the literature, two different performance parameters were measured: (1) level of presence and immersion, and (2) user task performance within the IVE. The workload for each subject was also measured as a tool to find out any relationship between the results of the measured levels of presence and immersion, and the user task performance in the experiment.

Even though we did not have enough data to test the experiment hypotheses statistically, the results of our study were used for initial evaluation for further testing in the future. With this being said, the results of our preliminary user study indicated that participants did experience a strong feeling of presence in both IVEs, and somewhat higher levels in the 360 Image Based than in the Graphical IVE. However, these results were not reflected in the same fashion for the user task performance results related to object finding and identification, as it was initially expected given the characteristics of a 360 Image based IVE. Participants performed better in the 360 Image based IVE in reading related tasks, but their performance in object finding and identification tasks was better in the Graphical based IVE. Ultimately, the difference in changes in performance ($\Delta_1 = \Delta_2$) between these environments showed that it is likely not significant, and therefore, both the 360-degree and BIM based IVEs could potentially be considered as an adequate representation of the built environment with the purpose of study human-building interaction with different applications such as in building occupant behavior in the design and post-construction stages. However, more data is required to perform the proper statistical tests and to generalize any findings.

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