A Feasibility Study: Exploring Design Using BIM-based Virtual Reality

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Abstract

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The use of Building Information Modeling (BIM) has been a growing trend in the architecture industry because it dramatically improves workflow, collaboration, data visualization and production costs. However, BIM has some significant limitations, particularly for clients and other non-experts who need to understand a design as it develops. For buildings not yet built, people are unable to experience the space physically, so most architectural representations—including those produced with BIM—project a virtual 3d environment on paper or on a computer screen. These 2D projections are often difficult for non-experts to understand, and 3D visualizations on a computer screen may still not support users' spatial perception. Virtual Reality, as the most immersive medium for visualizing a digital model, can offer people another way of understanding a project in terms of the feeling and perception of being inside a space. This thesis discusses the integration of BIM and VR, which excel in different areas, as a means of offering better representations of architectural projects.

An experimental research methodology is used to assess the effectiveness of BIM and BIM+VR environments for communicating building information to people who are not experts in architecture (such as potential clients or users). The study findings support the improvement of building representation in BIM models by applying VR technology, and suggest that the combination of BIM+VR supports decision-making in the preliminary design process by supporting potential users' perceptions of the space.

Keywords: Building Information Modeling (BIM), Virtual Reality (VR), 360° photo, Human perception, Design review

List of Figures

List of Tables

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Table of Contents

Introduction

Computer technology has a profound impact on the building profession. Building Information Modeling (BIM) is quickly establishing itself as a new standard for architectural practice because of its significant advantages: greater efficiency, improved communications and coordination, shorter project lifecycles. Almost 50% of the industry is using BIM, and its adoption will increase (Young et al., 2009). Therefore, many universities implement BIM courses to equip students to apply their knowledge and practical skills in the future job market (Astaneh Asl, 2019). It can be seen that BIM is a significant part of the whole building industry.

An architectural practice generally uses a systematic project structure involving a large number of technical and construction professionals, and their efforts are constrained by the pressure of the construction process, huge investment costs and long project timeframes. These enormous costs require architects to be very careful in the pre-construction design phase. Architects have to constantly analyze the feasibility of the scheme and make iterative changes to the model throughout the preliminary design process in order to avoid potential problems in the later construction process, which might cause serious waste of resources. Three dimensional (3D) modeling software enables architects to develop a completed model by using various geometric elements. But most 3D modeling software only allows designers to create 3D models with limited functions (animation, rendering and so on). Unlike 3D modeling software such as Sketchup or Rhino, the core logic of BIM is to combine detailed data about the properties of a building based on coordination of the construction process rather than the geometry of the model. BIM technology also allows all building performance simulation analysis to be completed in the model and offers the ability to implement simultaneous changes to shared data. This enables BIM not only to be used for visualization in many aspects of the design process but also to increase workflow efficiency for the project team.

Despite BIM's ability to improve visualization, its main contribution lies in the integration of multi-disciplinary and multi-dimensional information (W. Xiao et al., 2019). BIM still uses traditional modes of representation, including plans, rendered images displayed from a fixed angle or animations, which follow a prescribed path. These methods of architectural visualization are likely to limit people's understanding of the design. The pursuit of high-quality architectural visualization has been an important goal in architectural practice, but traditional architectural communication media such as physical models, rendered images and design documents can still be a challenge for nonprofessional viewers to understand (Chen, C.L et al., 2007). For buildings not yet built, people are unable to experience the space physically, so most architectural representations—including those produced with BIM—rely on a virtual 3D environment presented on a computer screen. Neurology studies indicate that 3D models in VR are less demanding on the brain than 3D models seen on flat 2D computer screens (Hermund, A et al., 2018). This suggests that VR technology can be utilized to change the way we interact with and interpret models, drawings, and data.

Virtual reality (VR) has a huge advantage in visualization over other modes of representation, since it extends the experience of space from a real environment to a virtual environment. It enables architects to build a virtual 3D scene in which they can roam, watch and experience facilities in the process of conceiving designs. By taking full advantage of the various human senses such as vision, hearing, and touch, VR allows designers to experience spatial relationships, dynamic light and shadow effects, and even sounds, and then make detailed adjustments. Nevertheless, VR usually simply works as a visualization platform that offers some viewing controls but no real interaction with the design object, nor does it contain technical data about the objects or buildings it depicts (Okeil, A. 2010). In addition, the price of a whole VR system can be too costly for many consumers. Therefore, 360° video—a technology using a smartphone inserted into simple goggles that allows users to experience a series of panoramic views from fixed positions in a digital model—offers a feasible and easy bridge to the immersive experience of VR at much lower costs.

On the other hand, BIM has high functionality and strong data integration capacity, but the visualization of a BIM model usually relies on 2-D computer screens and lacks sensory immersion, which may prevent the full utilization of the model (Zaker, R. et al., 2018). Considering these problems, it would be of great significance if architects could combine the power of BIM with the immersive experience of VR as a digital medium for architectural representation during the design process in order to coordinate and communicate with different stakeholders in the process. Although BIM and VR are highly complementary, they are rarely combined early in the design process.

Even in offices that make extensive use of BIM and other digital tools, architects generally do not understand how to apply VR to assist design decision-making. Thus, it is necessary to figure out what aspects of VR are relevant and actionable in design. Rather than focusing on VR system development and application, the work presented in this paper focuses on the benefits and limitations of using BIM+VR as a design support tool. In current architecture practice, if designers use VR, it is to present a completed or nearly completed project design to the client, who may not have participated extensively in the design process. This method focuses on the final result and does not differ essentially from traditional architectural representations (drawings, rendered images or animations). The main object of this research is to explore how to apply VR as a complement to the BIM platform to extend clients' participation in design workflow, so as to improve design efficiency. Additionally, through the comparison of VR and 360° photos, this thesis focuses on factors related to VR experience for non-experts, hoping to evaluate the effectiveness of VR+BIM technologies and make their combined use more effective in the architecture design review process.

Literature Review

Evolution of architectural visualization

During the design process, architectural representation is necessary for architects to communicate their ideas. Architecture development continues to be influenced by the use of computational technology, and representation has shifted mostly from hand drawings to digital images (Cao, Z. 2020). Architectural representation has undergone several significant reforms in the last 50 years: (1) from hand drawings to 2D drawings (AutoCad); (2) from 2D drawings to 3D models (Sketchup, Rhino); (3) from 3D models to building information models (Revit). Currently, architects are exploring the possibility of combining 3D models with immersive virtual reality for project representation.

Existing architectural drawing techniques describing buildings date back at least to the fourteenth and fifteenth centuries (Brakke, A. 2017). Many early drawings did not have scale or dimensions, although they contained textual descriptions to help people understand their intent. These sorts of drawings helped to manifest the buildings the architects visualized, but they contained many errors or inaccuracies, and could not convey three dimensional characteristics of buildings effectively. Very early artistic drawings and paintings of buildings did not accurately depict depth or foreshortening (Leslie Lienau, 2013) until linear perspective was devised in the 15th century by Filippo Brunelleschi and others (Talbot, R. 2003). Architects adopted this technique to convey volumetric and spatial characteristics of their designs during the late Renaissance. Later, the cartographic axonometric technique, which is much easier to construct than perspectives but is also effective for visualizing complex spatial arrangements, was developed by architects for depicting buildings, and was used widely during the late nineteenth and early twentieth centuries (Cocozza, F. 2017). Architectural models, which were used extensively during the Renaissance and later, offered the possibility of conveying the volumetric composition of the project (Romullo Baratto, 2016). These were often very accurate but costly to produce. Nevertheless, from the Renaissance onwards, physical models have been used to document architectural projects as aids to design and to make them more comprehensible to clients (Empler, T. 2018).

Computer technology was first used in the automotive and aerospace industries in the 1940s then widely spread to other fields. The term “Computer Aided Design” (CAD) emerged in the 1950s and is commonly credited to Douglas Ross, a computer scientist from MIT. Later, Ivan Sutherland invented SKETCHPAD, allowing users to interact with a computer device through visual aids, which took an enormous step forward in the field of human-computer interaction. Early 2D CAD programs used standardized plan, section, and elevation drawings for efficient information sharing among architects, constructors and clients. Compared with hand drawing, CAD technology has improved work efficiency, since it can speed up initial production of drawings and facilitate subsequent changes. Even as CAD systems have incorporated 3D modeling, the drawings they produce usually require some professional knowledge to interpret properly. For many non-expert clients, who come from other backgrounds and may not have professional training as architects, it is challenging for them to fully understand CAD drawings because they have to use their imagination to help develop a perception of what the drawings represent (Ching 1998).

With the advancement of 3D model tools, model elements can be coordinated so that design changes in one can relate to other parts of the model. With current modeling tools, it is also possible to work interchangeably with several different modes of drawing — plan, section, elevation, perspective and axonometric—with the added dimension of movement, which has become more fluid and useful as processing power has increased. Digital models also allow architects to communicate shape, structure, color, texture and many other factors of performance, so as to better establish visual communication between designers and clients. Precise lighting and camera settings as well as the realistic simulation of material can allow the renderings of digital models that are more accurate, and often more effective in revealing architectural thinking than hand-drawings. (Cao Z, 2020). The development of 3D model rendering allows architects to add furniture, human figures, subtle material characteristics, complex light effects and other elements in design that can help tell a fascinating story about a building, making the design idea more clear and easy to understand.

In 1974, Charles Eastman proposed a building database named Building Description System (BDS), which was the first software to describe individual library elements that can be retrieved and added to a model. This technique of representing the buildings through databases is the core concept of BIM (Vanessa Quirk, 2012). By assigning data information, architects tell computers how to transfer the basic elements in drawings (points, lines and surfaces) into building components (walls, windows, slabs). This method builds a close relationship between 3D models and 2D drawings allowing them to work together during the process. As another revolution after CAD, BIM not only provides a collaborative platform for computation simulations, but also the breakthrough of improving construction workflow efficiency. It deepens the interdisciplinary cooperation and communication during the architectural design process, which has a profound effect on architectural design (W. Xiao et al., 2019).

VR technology was first used in military and medical fields. However, it has not been widely popularized because of its expensive equipment and high requirements for computer processing. However, with the appearance of moderately-priced VR head-mounted displays (HMDs) for civilian use, VR has begun to develop rapidly in the fields of gaming, entertainment, education, construction and design (W. Xiao et al., 2019). The central component of virtual reality is the human user (Paes D. etl., 2017). Users experience three 'I' characteristics of VR technology: immersion, interaction and imagination (Virsabi). Immersion describes the sense of reality users perceive in the virtual environment, which is an important evaluation criterion for VR technology. Interaction refers to the natural interaction between the user and the virtual scene, which includes body or eye movements. Common simulators allow users to grasp, move, control, touch in the virtual world by working on the controller. Immersion and interaction are the essential difference between VR with other related technologies, like 3D animation. Imagination emphasizes that VR inspires humans' creative thinking. People improve their consciousness and awareness to context by using their initiative to explore the surrounding virtual environment.

360° photo or video, also known as immersive photo or video, uses specialized multi-camera equipment that can capture a 360° x 180° field of view instead of the limited viewpoint of a standard recording (Rupp, M. A. et al., 2016). Although both 360° photo and VR place the user in an immersive environment, there are many differences between the two. In VR, users are able to view the full panorama with an HMD, as if they were inside the real environment. This creates a high sense of presence and immersion. Participants can walk in the virtual scene without restriction of preset viewpoints or targets. They can access interesting or important places, which is consistent with our living reality. If a person crouches down in the real world, the computer will mimic his movement in the virtual world. This immersion leads to the stronger user interaction with the designed environment to elicit an emotional and psychological response (Maldonado et al. 2016; Riva et al. 2007). Many companies are working hard to improve the technology of VR output equipment (solving the motion sickness problem, improving rendering quality) to enable users to believe what they see in the headset is real. Nevertheless, the development of VR technology in the field of interaction is lagging behind, and the mainstream situation is to use controllers to interact with virtual objects. In 2D screen interaction, most control commands can be concluded as key or mouse actions. But people expect to interact more naturally in virtual reality; that is, people want to interact in the same way as they interact with objects in the real world. The touch and gesture interactions are particularly important in the user-centered concept of virtual reality.

By contrast, 360° photos allow only left-right and top-bottom viewing within an enclosed spherical space limited by the filmmaker's views, while VR allows interaction with the objects in simulated digital worlds (Ward 2017). Even so, previous research has found that 360° photos can also be highly immersive experiences that activate a sense of presence that engages the user to focus on the virtual content by making the user feel as if he or she is physically a part of the environment (Rupp, M. A. et al., 2016).

Although VR allows a great immersive experience, it also has some high-cost and complexity problems. Price is not the most critical factor, while high efficiency is the key. The application of VR requires cooperation with the computer and headset and this process can be time consuming. Thus, the new, light, wireless VR headset has gradually become a development trend. Some 360° photo equipment, such as Google Cardboard, offers a good, fast and easy way to interest the public to use VR. Through 360° photo environments, participants can view the 360° panorama content by moving or rotating the device in which the content is played, such as a PC, smartphone, or tablet (Repetto et al., 2018, Ventura S, etal., 2019). Architects can view 360º panorama images in VR and immerse project stakeholders in the design in a couple of minutes. However, the phone-based 360° photo headsets, including the Google Cardboard, can only track people's head's orientation, not its position, and most lack fine control over display timing (Christie Hemm Klok, 2015). Participants are more like external observers in 360° photos, but its strength lies in cost and time advantages: the design team only needs to provide simple 360° photo glasses for multiple users watching virtual scenes at the same time. However, this experience is “one-sided” since users can only view the static space. Many researchers claim that the more immersive VR provides overall better spatial perception over 360° photo (Ventura S, et al., 2019, Paes D. et al., 2017).

Opportunities and Challenges for Architects in Design

If you were to ask an architect “where is it most important not to make a mistake in architectural design?” the architect may reply with many professional answers such as: building structure, lighting, spatial scale, and so on. A non-designer might not be able to answer this question clearly, but that does not mean they are unable to perceive design mistakes when they encounter them. If we were to introduce a non-designer into a house that is full of mistakes, they might feel the fault of ill-proportioned stairs, a misplaced door knob, or a badly-designed banister before actually seeing it. Every ordinary person is an expert in these architectural elements, because they have stepped on stairs and touched door knobs and railings countless times in their daily lives. People have a keen sense of which architectural spaces are comfortable and which are not, based on their own life experiences and personal perceptions. Dimensional perception and understanding of space are therefore critical factors for architects to understand as they make design decisions (Astaneh Asl, 2019). It is possible to improve design and reduce rework if the architect and clients review the building space from the first-person perspective at the early stages of design.

Rework is very common in building projects. Rework can result from both objective and subjective factors. Objective factors include errors, omissions, failures, changes, while subjective factors include changed requirements, poor communication or coordination (Palaneeswaran, E 2006). Rework can be more than simply irritating; it is a productivity killer and often causes missed deadlines and budget overruns. Previous studies concluded that costs of rework can add around 10% to the total project costs (Palaneeswaran, E 2006). VR can help avoid this, because designers and clients who can communicate through a VR environment are likely to understand the real experience and avoid a final result that is not in line with the plans.

Different people on a project team, even if they are all architects, might have different 3D space imaginations and image recognition ability. In general, people tend to have a field-dependent cognitive style, a concept illustrating that learners are most affected by their environment and tend to rely on information provided by their familiar world (Witkin H, 1962). That is why most people prefer to accept and understand box-like buildings, since most buildings are regular in reality. People can have difficulty visualizing irregular shapes, such as curved walls, columns or slanted architectural features, because they are abstract and demand great space imagination. Particularly with complex building projects, designers need to communicate the design ideas and thoughts accurately to the others. VR technology can contribute to solving this problem, since it facilitates spatial conception (W. Xiao et al., 2019). It is often difficult for people to immediately interpret architects' 2D renderings, so usually architects have to explain a lot about what their drawings show, but VR finds a new way to bring the design to life, so clients can see the logic of the design layout from an immersive point of view. High-quality architectural visualization is an important goal in architectural practice. Excellent visualization makes it easier for people to understand complex building systems and design changes in an intuitive way, which is beneficial for further decision-making.

Today architects have more choice to depict their ideas with updated digital technologies, and VR is one excellent choice because it can affect subjective feelings in ways a BIM information cannot (WQ Guo, 2017). BIM + VR utilizes VR technology to carry BIM models and data, it also can help visualize BIM data, such as collision detection, light analysis, sunlight analysis, etc., which can greatly improve the uses of traditional BIM. Compared with 2D rendering tools, VR displays BIM information in a more realistic way, thereby potentially increasing participation by project stakeholders, including architects, clients, project management, operators and so on. Table1 compares the characteristics of different setups and shows that a BIM+VR platform can integrate data with multi-dimensional interactivity, thus making synchronous changes possible and receiving feedback in real time.

Table 1 - Comparison of different architectural representation methods

Comparsion of different architectural representation methods

Method	Sensory				Motion		Interactivy	Datas
	Vision	Hearing	Smell	Touch	Static	Dynamic		
2D drawing	Yes				Yes			
BIM	Yes				Yes			Yes
VR	Yes	Yes		Probably	Yes	Yes	Yes	
BIM+VR	Yes	Yes		Probably	Yes	Yes	Yes	Yes

VR Technology Enhances BIM Strength

As a building project passes through different phases, increasingly parameters are added to the existing information contained in BIM. These additions can be defined as BIM dimensions (Sampaio, A. Z., 2018). In order to better serve building projects, BIM software designers have been working on extending to more dimensions and developing BIM to become a powerful construction planning and management tool. Different dimensions have their own purposes and roles in the project. However, all these analyses happen on the computer screen where the 3D model is projected on a 2D display, so people review the building model from the bystanders' perspective, and they are often unable to perceive the size, scale, lighting, textures, colors, of the proposed building in BIM. For example, BIM presents 3D models or 2D drawings on a 2D screen where it is difficult to incorporate human figures effectively in space. Human figures are helpful for architects as they study buildings in representations, because they can quickly associate the familiar shape and size of the human body with the dimensions of things that surround it (Anderson, A. T. 2002). Without people, the building looks empty and incomplete, and it can be hard to visualize how large or small an area actually is. Another challenge with BIM is that usually only one person has the control over the viewpoint and can create markups in BIM software, and the low-level participation of other people may affect the efficiency improvement.

VR allows interaction with 3D BIM models in two important ways: walkthrough and consulting data. Walkthrough is a method in which people can view the building model from a first-person perspective and move freely within the virtual scene. Consulting data represents the possibility of retrieving information from a centralized model in a virtual environment (Sampaio, A. Z.,2018).

VR has the ability to make the scene more believable to the audience because it simulates how we perceive surroundings in everyday life. Neurology studies indicate that three-dimensional models experienced with immersive VR are less demanding, cognitively on the brain than three-dimensional models seen on flat two-dimensional computer screens (Hermund, A., 2018). This suggests that it would be easier for people to extract and process information from VR environments than from conventional 2D screens or pictures, which indicates that there is the value to bring VR to the design review meeting with architects and clients.

A BIM model contains a great amount of data, including geometrical information as well as mechanical, electrical, and plumbing systems. It can also include cost schedules, GIS data, water runoff, lighting, etc (WQ Guo, 2017). A big project requires many specialized staff and no one can be specialized in fitting all the data together, let alone some stakeholders, such as clients, who may have no familiarity with construction documents. For many users of the BIM model, it may be more convenient to explore BIM data in a virtual environment. Coordination of BIM with VR could help people to overcome the barriers of understanding complex data in the model. In the VR scene, for example, people could navigate the building model and quickly define the data source or interact with data by clicking or touching on the object itself (Astaneh Asl, 2019). The BIM model in VR can also be visualized with an overlapped window, where the user has the ability to retrieve its data when encountering a unique geometric representation (Sampaio, A. Z.,2018). This could be an easier way to help people query data at the building element scale, and the modification made in the virtual world can be synchronized in the BIM model. So, the aspect of linking the data consulting capacity and the VR ability of walking around is an essential improvement in the use of BIM for non-experts (Sampaio, A. Z.,2018), because now data is not just the simple number, but something that can be visualized as part of an immersive experience.

A data accessible BIM model in a VR environment can serve as an essential communication tool for real-time decision-making. Previous research has found that a construction project team prefers to have face to face (F2F) meetings in the same place (Ali Abbas et al., 2019). The F2F meeting allows members to see others' facial expressions and body language, and drawing and sketching together also contributes to improved communication efficiency (Astaneh Asl, 2019).

However, these advantages can’t exist if the team has to work virtually. Although BIM provides several ways to mark up the model in a remote meeting setting, it only allows one person to share the screen and use the markup tool. There is one leading software for immersive design review and collaboration in virtual reality named IrisVR, which is an annotation tool that allows each individual to mark, brush, highlight and measure a model when they enter into VR space. They can also use callouts or add notes onto a surface, as Figure 1 shows, making it easier to call attention to some aspects of the design (Figure 1) . In the context of linking data in the virtual world, many people can be connected into a shared virtual environment at the same time. Designers can modify materiality, lighting, and physical geometry data based on participants’ on-site feedback, giving confidence to decisions and reducing stress for uncertain rework.

Figure 1 - Callout tool in IrisVR environment

(Source: https://help.irisvr.com/hc/en-us/articles/213570187-Annotations)

4D BIM models allow participants to extract and visualize their construction progress throughout the life cycle of a project by integrating models with time. The time concept in 4D models has been shown to bring benefits to optimize construction activities, personnel deployment and team coordination in management processes. However, architects are more concerned with time to be a dimension for design. Design and time can be regarded as two elements of mutual cause and effect: time can be one consideration of design as well as the design representation. The model in VR can be dynamic and interactive, allowing designers to explore hypothetical scenarios, observe changes in space with time and make corresponding adjustments in materials, connections or path design. Also, scenarios can be assigned to extraordinary events such as an evacuation. Dickinson, P. et al.,(2019) used crowd density as an independent variable to test its impact on user experience and behavior in VR simulations. The final result indicated that participants respond to crowd density in VR in a comparable way to real crowd situations, which means human response in the real-world can be simulated in VR settings. This suggests that designers can invite participants to be surrounded in BIM-VR environments at different times and record their cognitive performance, psychological status or physical behaviors. For example, designers of a school project can invite students to experience their daily life in classrooms in VR before the school is built. If a student reflects that a corner in a classroom is normal throughout the day, except for having strong sunlight reflection at 3 pm, then architects should consider readjusting the position of windows. On the one hand, the function, space, form, environment of a building will change continuously through time. On the other hand, the human experience for architecture is formed through physical movement, different sensory stimuli, and the changing landscape. Therefore, the time factor cannot be ignored in the architectural design process and VR can compensate for this deficiency of the 4D model in BIM.

The only simulated sense in current BIM practice on screen is sight. It does not simulate other senses, which help users understand and perceive the world around us. VR extends the experience of space from a real environment to a virtual environment. Because BIM contains complete information that is highly synchronized, it has enough data to build a detailed VR scene, in which people can roam, watch and experience facilities, even as they are in the process of conceiving designs (WQ Guo, 2017). By taking full advantage of the various human sensory experiences, VR allows designers to feel the change of spatial relationship, light, shadow, and even sound effects, and then make detailed adjustments (W. Xiao et al., 2019).

In addition to sight, current VR practice can affect hearing and touch. Since smell and taste are hard to simulate, they are not currently included in VR scenes. Addressing hearing is great for designers to discover psychological benefits for building occupants, such as the soothing sound of a stream and its effect on someone’s experience of a space. Touch and movement can be used for space inspection and path simulation. For example, using VR, architects could conduct a path simulation by inviting users to “walk” in a building model to find design problems, or to test spatial arrangement and signage for way-finding (W Xiao et al., 2019). Multiple sensory combinations enable architects to discover blind spots which are hard to discover on 2D screens.

Despite its potential, touch sensitivity is not often used because of the high cost of tactical gloves and jackets that could simulate the touch sense, and because current VR systems lack the ability to convey realistic haptic (kinesthetic and cutaneous) sensations (Otaduy, M. A. et al., 2016). Moreover, architecture firms would generally find the complexity of programming and configuration in processing VR models to be too difficult. For example, Unity, a tool for representing touch in 3D scenes, requires C# coding script to achieve a complex VR touch control system. This aspect of VR is likely to become easier to implement in the future.

BIM+VR brings interesting potentials to architectural design and offers the opportunity to explore virtual spaces freely. The advantages of BIM+VR are not only limited to better visual effects, but they offer the possibility of consulting model data while also improving perception of the proposed space while walking through a virtual building.

Table 2 - Comparison of BIM and BIM+VR

Comparsion of BIM and BIM+VR		
	BIM	BIM+VR
Model	A building data information model	Display building data information model based on the virtual reality platform
Time	Visualize construction progress throughout the life cycle of a project by integrating models with time.	VR allowes people to explore dynamic scenarios and observe changes in space with time
Collaboration	throughout the life cycle of a project by integrating models with time.	Sharing the models in the cloud and stakeholders can experience the model in the virtual environment and comment
Correlation	The model, drawings and data correspond to each other and all modifications are updated synchronously	VR reads the attributes of components in the BIM model. The modifications made in BIM and VR can be updated synchronously
Perception	Only obtain information from the view and lack the simulation of other senses.	VR extends the experience space to immersive environment, which people can roam, watch and experience

Exploring Immersive Environments for Human Perception in Architecture Design

A building project can be decomposed into several tasks: Preparation, Design, Preconstruction, Construction and Operational Use (W Xiao et al., 2019). There are many use cases of VR for the building industry. For example, operators use VR as a training tool for building operations in the preconstruction phase. One real power in implementing VR technology should lie in the design process itself. However, VR allows designers to jump into the “real operation” of a building and review the space design from the standpoint of human interaction and perception (W. Xiao et al., 2019). Human scale and perception are core standards to evaluate in space design. Designing to “human scale” means design that is optimized for human use (Justin Van, 2018). The verification and evaluation of scale in an unbuilt space can be a difficult problem at the initial stage of building design (J Ryu et.al, 2007). But space perception is unique and subjective and is hard to be quantized or judged. Many scholars have studied the application of VR technology in the context of space cognition. One previous study illustrated the strength of using immersive VR to aid people's comprehension of complex spatial arrangements in structural engineering (Fogarty, J et al., 2018). The authors conducted several experiments to show that students can understand construction projects and plans much better in a full-scale virtual environment supported by other design visualization media, such as drawings, digital models, renderings, and maps in comparison to traditional media (Messner J I et al., 2020). The research results of M. Chao (2020) in University of Chongqing showed students have more accurate control over spatial size and proportion and improved ability to understand spaces under the VR design mode than traditional teaching mode. However, it is worth noting that many previous studies focused on VR but take little notice of the impact of 360° photo in architecture design. Although VR has made great progress, there is still one major hurdle to overcome: cost. A completely smooth VR system always requires high-end graphics cards, an expensive headset, as well as the rest of the computer's internals. Take the Oculus Rift and the HTC VIVE as examples, which are the two best PC-tethered VR headsets on the market. The Rift is $399 while the VIVE is $499.

Generally, VR offers the best VR experience, which includes realistic picture quality, stereo sound effects, and a tactile feedback system, but it is too costly for many consumers. Therefore, enjoying great VR experiences at much lower costs becomes a VR growth driver. Currently, Google drives inexpensive mobile VR growth with its launch of Google Cardboard, where 360° photos can be experienced with a smartphone and cardboard goggles that only cost $10. Through 360° immersive environments, participants can view the content by moving or rotating the device in which the content is played (Repetto et al., 2018). Although the 360° VR photo is cheap and simple, its contribution to the human perception of virtual space remains questionable because users are only external visitors without control of the model, or much of their own movement within it. On the other hand, its immersive feeling is still superior to traditional visualizations (picture, model).

Many studies support that VR technology has a positive impact on spatial cognition (Paes D. et al., 2017; Lukačević, F et al., 2020, Repetto et al., 2018), but most of them focus on architectural education on campus. There is less quantitative research on people who are not experts in architecture (such as potential clients or users). To some extent, a building is a product developed for end users instead of architects. Therefore, it is important to focus on the feelings of users in space. Considering that most people are nonarchitects, the abstracted design documents are difficult for them to understand, and traditional visualization such as 2D pictures lack some degree of immersion. In this situation, VR offers a new opportunity to eliminate these problems. Frost and Warren found that VR can enable untrained participants to see and understand things they would not have been able to understand using traditional presentation tools (P . Frost et al., 2000). VR is an efficient tool for providing feedback of the 3D characteristics of the design object such as scale and proportion (Okeil, A. 2010), and the rapid acquisition and visualization of 3D characteristics makes it possible for non-experts to understand functions, spatial configurations, dimensions and dimensional ratios.

The VR equipment is heavy and expensive to use while 360° photo offers a relatively cheap and easy bridge to the immersive experience. However, most people are highly sensitive to the slightest dissonance between the movement detected by their inner ear and the motion that they see with their eyes, so any imperfect design of VR can make users physically ill (Christie Hemm Klok, 2015). The 360° immersive photo puts users in an enclosed spherical space limited by the filmmaker's views, and its VR headsets, including the Google Cardboard, can only track users' head's orientation, not its position (Christie Hemm Klok, 2015). Some scholars considered this experience not to be realistic and say it cannot be defined as a true VR experience (Christie Hemm Klok, 2015; Rupp, M. A. et al., 2016). However, 360° photos are on the rise and are a great investment opportunity today (Alex Pryor, 2018). It still can generate high-quality content that is immersive and can be light and portable at the same time; it just requires a mobile phone.

Unlike students, those clients and other non-experts, who are not trained as architects or designers have not received architectural education, it is difficult for them to mentally transform 2D image to 3D space, so their cognition about space mostly is based on their own life experience rather than the specific design itself. However, it is these less experienced or less expert people who could be final decision makers for a design. Architects have the responsibility to pass their design ideas to clients. VR can provide a representation method that eliminates information encoding and decoding between 2D and 3D and this could be very useful for non-expert clients (Okeil, A. 2010). VR has also been proposed as a solution that mitigates the cognitive load needed for the visual perception of spatial information (Paes D. et al., 2017).

However, how to weigh the pros and cons of VR and 360° photo for clients still needs further discussion.

Research Statement and Objective

BIM provides data covering the whole life cycle of a building, and it integrates different professions in the process. There are two key words in the name of BIM (Building Information Model): model and information. The model presents the “appearance” of a building while the information is the real “soul”. The biggest advantage of BIM does not normally lie in achieving realistic visual effects for commercial communication; its main strength is as a data aggregator for the design, construction and maintenance of buildings. However, whether people, especially those who don’t have a professional background or close familiarity with BIM, can correctly understand the information in BIM is open to question. For example, an ordinary person has difficulty judging whether a 750mm high table or a 900mm high table is more in line with the scale of the human body when presented only with numerical data. For professionals using BIM, even if all building components are built exactly according to plan, the final result may be unexpected. VR can offer an interactive virtual space experience that is closer to real life by rendering the BIM building model realistically. This can help people better understand the practical content of building information contained in the model. The following study has been developed to examine how VR helps people more deeply understand a proposed building design developed in the BIM environment.

Usually, architects rely on the high functionality of BIM to make the design cycle quick and intuitive, but the representations produced by BIM software are static and tend to show only selected angles of the design, particularly for clients who might be considering a design as it is being produced. In addition, these images cannot represent the effect of movement and change over time (Okeil, A. 2010). Previous research in the field does not discuss extensively how VR and 360° photo improve the ability of clients and other non-experts to understand a building project during design review compared with conventional desktop-options. Furthermore, many experiments related to VR rely on observations, surveys and interviews with students to understand the applicability of VR in architecture education (Nikolic, D. et al., 2019). Since people want to utilize the high functionality of BIM and the capacities of VR as a design support in actual projects, it is very important to determine whether VR actually helps clients better perceive the space and form of a design in its early stages.

Zaker, R et al., argued that the computer industry must make VR technologies more affordable or cost could be the main obstacle to its wide adoption. One question this study addresses is: considering the high cost and complexity of VR, is 360° photo combined with BIM a good substitute? Software developers in the AEC space are constantly developing 360° photo platforms that allow project teams to use mobile phones, tablets, and headsets to immerse themselves and their clients in their forthcoming buildings. James Benham, the CEO of AEC software developer JBKnowledge, suggested that AR and VR technologies are less likely to replace than to supplement CAD or BIM technology. It is more reasonable to make AR and VR technologies for the iOS and Android app SmartReality, which works with many 3D software programs, including Revit. It seems possible to integrate 360° photo and BIM into architecture design review. But whether BIM + 360° photo empowers human perception as well as BIM+VR, even with limited investment and equipment, is still unclear.

This study chose a simple lecture theater as a starting point to analyze people's understanding of sight-lines and spatial design based on representations produced using BIM and BIM +360° photo and BIM+VR. The lecture theater in this experiment is a large room typically used for instruction, generally with tiered seating that enables those sitting at the back to see what is happening at the front. A well-equipped lecture theater is good for concentration and learning experience. The key design consideration for a lecture theater is visibility, so that every person in the audience can see the person(s) presenting without an obstructed view. This depends on seating arrangement and the floor slope. While this experiment addresses sight lines, this is not the only criterion for a great learning environment; illumination, acoustics, and ventilation also matter (W. Xiao et al., 2019).

This study is a quantitative, comparative, user-centered methods study to explore the impact of different VR modes on the way non-professional users experience a virtual space designed with BIM. One of the greatest challenges in the design process is communication between designers and clients using models and drawings. In recent decades, digital representations have supplemented or replaced these tools. However, because visual communication in design is often constrained to 2D computer screens or print-outs, it can be difficult for different people to fully grasp the real implications of a particular design solution. The general use of VR systems has not yet become regular in the construction industry for several reasons: lack of image quality, high cost, the requirement of high-end PCs, and a lack of end-user perspective in the development of the technology (Atkins, J et al., 2017). Therefore, architects must consider the balance between the costs and benefits of using VR. This research considers some of the costs and benefits of VR, using an experiment in which some subjects evaluated different drawings of a BIM model on a computer screen, while others used Google Cardboard or HTC VIVE headset as well as BIM to move through and experience the model. This experiment examines the effectiveness of using BIM+VR in a simulated design review, while also considering whether a lower-cost 360° photo system compares favorably with a more expensive VR setup.

To summarize, this study generates the following research questions:

- How can VR+BIM affect the design review compared with BIM-only?
- What are the effects of VR on non-experts' spatial perception?
- What is the difference between the capacities of VR and 360° photo?

Research Methodology

Architectural design has an inseparable relation with scale; thus, it is important to accurately visualize this aspect of space. In some cases; architects use building codes or commonly accepted standards to design spaces and elements within them. For example, it is generally easy for architects to choose a 150 mm stair rise in a lecture theater design to meet sight-line requirements, since this is a typical size of stair used in lecture theaters. Multiple studies (such as GB 50352-2019) have demonstrated that a stair of 150 mm is reasonable. Nevertheless, there are many other scale designs that cannot be simply decided by building codes; in large sports buildings or complex theaters, for example, the design of sight lines is much more difficult. A good sightline design could offer the audience a satisfactory view of the performance, which is part of the overall qualitative experience. Currently the design criteria of the sightline is worked out after repeated deliberation between computer simulation and industry application. Since the sightline evaluation is hard to be quantized during conceptual design, architects always extract experience from the real application and improve it next time. Similarly in a shopping mall, or an exhibition hall, it is challenging to choose an appropriate scale. People's spatial experience depends largely on the scale of the surrounding environment. If the space scale is not well handled, it can have a negative impact on users' feelings. And, because it is very difficult to change the scale of an existing space, architects must repeatedly weigh the appropriateness of the scale early in the design stage. However, it is not clear that available visualization tools convey a realistic sense of scale and simulate sightlines in virtual space. One important aim of this experiment is to test the effectiveness of tools for scientifically simulating scale with virtual models.

The general objective of this study was to explore subjects' perception of a BIM model with particular visualization tools, so we compared how well participants could understand the scale of a space and its sight lines using BIM only, as well as BIM with 360° photo and VR setups. Each subject examined four different BIM schematic models simulating the early design phase of a project. These were identical except for the floor slope and corresponding stair heights, which in turn could affect people's field of vision from the rear seats. Therefore, the experiment questionnaire queried the subjects' perception of the step height in the lecture hall and their view toward the speaker's platform. The design of sightlines in a lecture hall usually involves three major aspects: distance, angle and slope, which affect the viewer's visual clarity, range and comfort (W. Xiao et al., 2019). This study only considered the slope factor. Generally, the steeper the slope the less that people's views in the back row are blocked by the people in front of them. However, a slope that is too steep will make people feel uncomfortable and may also be dangerous. In this study, the step heights of the four models were 0mm (model A), 150mm (model B), 250mm (model C), and 300mm (model D). According to the Code for Design of China Civil Buildings (GB 50352-2019), the height of a single step in a densely populated building with heavy traffic should not be greater than 160mm. Therefore, only the step height of model B is appropriate in real life. We assume that most people can quickly figure out that the 150mm step height is most comfortable and reasonable compared to 250mm and 300mm steps in real life, since people use stairs of approximately 150mm very frequently.

The study had several hypotheses:

1. The HTC VIVE would have the most immersive experience, followed by the Google Cardboard, and BIM only, but using HTC VIVE would be more discomfort than Cardboard
2. Subjects using the BIM+HTC VIVE setup would be most likely to judge model B favorably
3. The more immersive the simulation setup is, the more likely it can motivate people to offer choices and thoughts that are close to reality.

This study was approved by the University of Washington IRB Committee, with registration number STUDY00012342.

Research Settings

This experiment used Autodesk Revit as the modeling software to create and refine 3D models in the BIM environment. After all the 3D content was developed, the models were uploaded to VR software to make them interactive in virtual space. The experiment used two types of VR: 360° photo with Google Cardboard and a mobile phone, and VR with an HTC VIVE headset and a personal computer. Since the strengths of BIM lie in its clear and straightforward drawings and data, this study integrated BIM and VR set up together. Subjects were able to compare the VR models with the BIM models again after experiencing VR space and make their own final judgment, whether they were in an immersive or non- immersive environment. The results indicated that both VR and 360° photo enriched users' perception of scale. But only VR performs well in helping users to evaluate sightline design in different models.

Google Cardboard

The 360° photo setup in this experiment requires a mobile phone and Google Cardboard. Cardboard is a 3D headset made with folded cardboard that holds two lenses that, paired with a smartphone, creates a VR device. The field of view of Cardboard is 80°, and it works by displaying calibrated left and right eye images on the smartphone and focusing these on the eyes using the lenses to give the subject a stereoscopic view, while the gyroscopes in the phone are used to follow the subjects' head movement when they look around. Although Cardboard is a feasible and convenient method to enable the public to have a chance to enjoy VR experiences, it can only track the user's head's orientation, not its position, and most lack fine control over display timing (Christie Hemm Klok, 2015).

This experiment uses Modelo software to convert the 3D BIM models for use in Google Cardboard. Modelo is an easy and fast platform to use. Architects can upload the converted model to the cloud and quickly share it with team members and clients so that everyone can view the model and express their own opinions about it. The 360° interactive dynamic panoramic images generated in Modelo are imported into the mobile phone, and the mobile device is put into the Google cardboard headset to realize virtual scene roaming. The visual quality of mobile VR experience depends on the fine degree and the details of the panoramic image; generally, the more detailed and realistic the image is, the more realistic the VR experience would be. However, this system does not allow people to synchronously incorporate their body movements into the virtual environment; they can only observe the virtual world from fixed positions while moving their head to negotiate the 360-degree panoramic image.

Figure 2 - Google Cardboard and Modelo

HTC VIVE

The hardware used for VR in this experiment is the HTC VIVE headset. HTC VIVE is one of the main VR devices in the market; it offers realistic picture quality, stereo sound effects, and a tactile feedback system. The field of view of the HTC VIVE is 110°, which is 30° wider than the Cardboard. A wider field of view assures an immersive and realistic experience. It allows users to interact with and navigate through the virtual world using two handheld remotes, and they can look in any direction they want. The researcher imported the BIM model into Enscape, a VR rendering platform with a complete material library and the prominent advantage of simulating real physical states, on a personal computer to finish the VR scene, then connected the HTC VIVE into it. The advantage of VR lies in its strong sense of immersion and realism it provides; however, the cost of the headset is high, and it requires an expensive computer, since a high-power graphics processing unit (GPU) is necessary to run the complex VR scene.

Figure 3 - HTC VIVE and Enscape

Pilot Test

Before the formal experiment, the researcher conducted a preliminary test with a limited group of people to identify potential issues in the process and test the effectiveness of questions. At first the researcher only gave subjects three models of a lecture room with different floor slopes (using stair heights of 0mm, 150mm, 250mm), and the result showed that all of the subjects chose Model B (height = 150mm) as their preference, regardless of which tool they used. Then the researcher realized that with three choices, people tend to choose the one in the middle because they feel it is most "safe". This behavior is consistent with extremeness aversion, which is the tendency of choice makers to avoid extreme options and choose an intermediate option (Padamwar, P. K et.al, 2018). For example, when a magician asks a volunteer to choose a card or a cup, they almost always choose the middle, rather than one of the two sides. Therefore, for this experiment, a fourth model was added in order to avoid this bias and reduce its effect in the formal experiment.

Figure 4 - 360° photo(left) and VR(right) scene in pilot test

Model Developments and Questionnaire

The research experiment places participants in a series of four lecture hall models with different slope gradients. The four models are otherwise the same. The height of the steps in the four models are 0mm, 150mm, 250mm, 350mm. This study emphasized slope as the only variable because the floor slope is a crucial determinant for sightline analysis, which is an essential topic for lecture hall design. The intention of this experiment is to determine how VR technology influences the decisions people without professional architectural knowledge make about the effectiveness of a lecture hall design

There are 14 rows of seats and a platform stage in the lecture hall. In the models with a sloped floor, the steps start from the fifth row. Except for the last row, a 3D character is placed in each seat to simulate the front seat's view blocking the sight of the seats behind it, as in a real-life crowded situation in the lecture hall. There are three highlighted seats in the last row, and participants were asked to check whether they have a clear view of the front platform from these seats. The purpose of leaving the last row of seats empty is to ensure that participants will not feel like they are using an occupied seat when observing the virtual world.

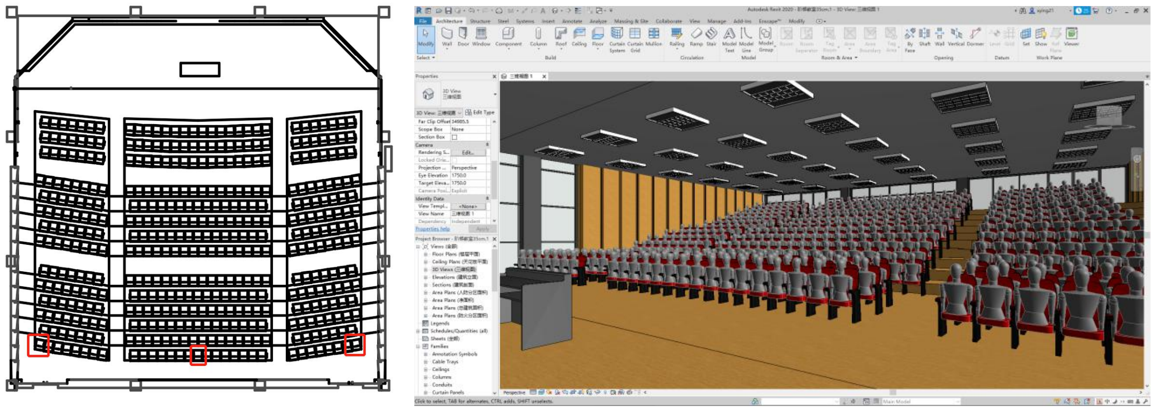
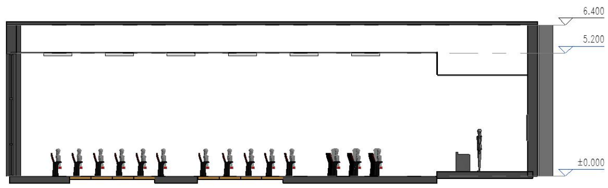
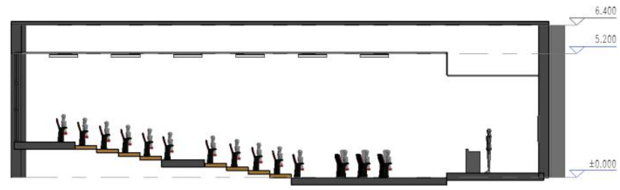


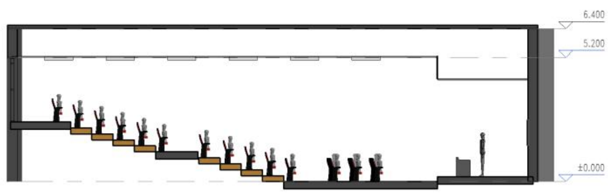
Figure 5 - The plan and 3D view in Revit of Model D



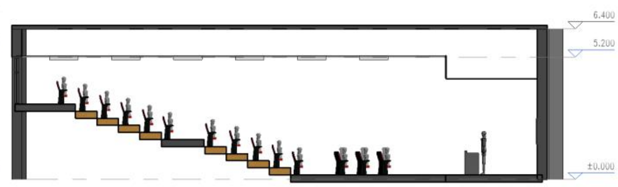
Model A (Step = 0 mm)



Model B (Step =150 mm)



Model C (Step = 250 mm)



Model D (Step=300 mm)

Figure 6 - Sections of 4 models

The experiment collected two types of information, relating to user experience and user behavior. User experience included specific (participants' satisfaction toward different models and setups, evaluated through Likert-scale-based questions) and non-specific factors (feedback in the open questions of the questionnaire), while data on user behavior included observations recorded by the researcher of subjects' operation process, travel routes and amount of time they stayed at each spatial point. The questionnaire was designed to study participants' ability to identify and evaluate spatial characteristics, such as materials, distances and heights in different environments. The answers were helpful to identify what features were popular or unsatisfactory in the BIM and VR environments and the pros and cons of 360° photo and VR. In addition, this experiment addressed the question of whether a high quality representation of spatial elements (shape, depth, shadows, textures, light) in the VR environment enhanced the subjects' understanding of the virtual space.

Research Development

The COVID-19 pandemic resulted in closing the University of Washington campus, so participants could not be recruited at the university. Instead, most recruitment work occurred remotely in China by sending recruitment advertisements in a WeChat group chat and contacting subjects through email. Finally, 33 subjects participated in this experiment, and most of them did not have any architecture background. This is a positive and meaningful factor, since the intention was that they should act as "naive clients" in the experiment. Although they did not know too much about architecture, most of the subjects had relevant prior experiences with 3D models and VR. All participants were randomly assigned to one of three groups.

All participants were told that they were going to be given free time to observe and experience four lecture hall spaces (but they were not told in advance where the difference between the four was). The participants were encouraged to ask questions during the experiment. Group A could rotate the digital model using the computer mouse to view it on a computer screen from any perspective they chose. They could also query building elements' data in Revit. Groups B and C could also explore the space in both VR and BIM environments switching freely between these as they wanted. Before subjects began the actual study, they familiarized themselves with Revit and VR through a "pre-test" model. For the mobile VR group, since the Cardboard headset has limited user-input capability and is only used for passive viewing of 360 degree images, the experiment involved pre-set panoramic images of subjects' seating views (in the left, middle and right seats of the last row) and walking views (stand on the stage and the first stair) for the mobile 360° photo experience. Participants could switch scenes by pressing the button on the side of the Cardboard headset in the formal experiment. With the phone in the Cardboard headset, subjects could view panoramic images through the lenses in the two eye holes and turn their head for a 360 degree view.

For group C, it took a lot of time to help participants adapt to the HTC VIVE headset. We needed to adjust the headset position to make it comfortable and to enable each subject to have a clear view into the virtual space. The different configurations for each user made this process tedious and time consuming. The participants were able to simulate walking and movements by turning their head or using controllers. In reality, these subjects stood in an empty room because it facilitated full rotation of the body, and it allowed subjects to walk around and look in any direction in the VR model. Subjects entered the lecture hall from outside and could walk around and explore the room from any viewpoint if they wanted to. Once the subject was ready to proceed to the next model, the researcher would instruct them to experience the next one.

After the test, all participants were asked questions about their ability to assess qualities of the space, such as materials, distances and heights in different environments. They also answered a series of questions positively or negatively about their view from the seats. In addition, they were asked to answer how VR mockups and BIM models helped them understand the design of the space.

This research included two sets of questionnaires A and B. The questionnaires were written in English and translated into Chinese since this study was conducted in China. The participants were asked to evaluate 4 lecture halls from the standpoint of a client, and to pick up their favorite one. Questionnaire A was designed to collect personal data anonymously; its questions only included age range, education background and previous architecture experiences. Questionnaire B focused on obtaining subjects' evaluation and opinions of BIM and VR. It asked subjects to estimate the room width and assess their environmental perception related to two statements: (1) In Model A/B/C/D, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without visual obstruction (2) I think the gradient (stair height) in Model B/C/D is appropriate and well adapted to the human scale. This question used a Likert-scale question ranging from (1)strongly disagree to (7) strongly agree. In addition, we also required participants to use a Likert scale to evaluate how different setups helped them perceive the space. Some typical questions were: "BIM + MVR(PCVR) is very helpful for me to estimate the depth/width/height of the room", "BIM + MVR(PCVR) is very helpful for me to realize my location in a room". Questionnaire B also included questions on how BIM and VR helped participants understand the model with regards to several aspects, including material, color, location, distance between seat rows. Finally, there were some open questions at the end of the questionnaire to ask participants to think about to what extent the VR mockup and BIM were helpful in allowing them to understand the architectural design. In addition, the researcher also took notes of the subjects' oral feedback during the study. After all tests were over, the researcher collected all paper questionnaires and recorded and analyzed all the data in digital form.

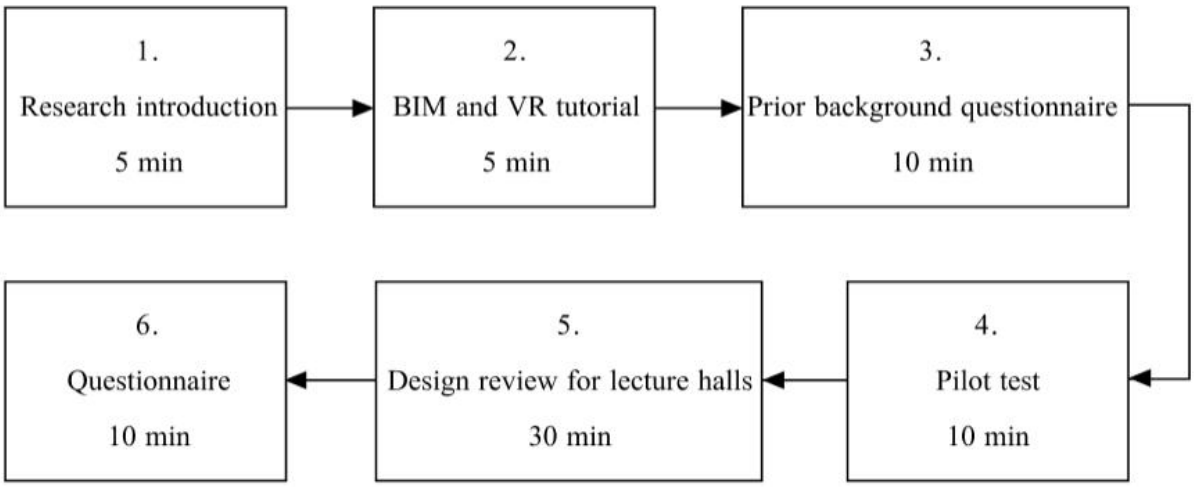


Figure 7 - Experimental procedure

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1 = Strongly disagree, 2 =Disagree, 3 = Somewhat disagree, 4 = Neutral, 5 = Somewhat agree, 6 =Agree, 7 = Strongly agree Stair A = 0mm, Stair B = 150mm, Stair C = 250mm, Stair D = 300mm,																			
	Subject	Age Range	Education	Arc Backgr ound	Game/3 D Exp	VR Exp	Estimati on	Quick	A(sight)	B(sight)	C(sight)	D(sight)	B(stair)	C(stair)	D(stair)	Recogn ition	Material	Locatio n	Distanc e
	1	18-25	High school	N	Y	N	Small	5	3	4	5	6	4	5	4	5	5	5	3
	2	26-35	High school	N	Y	Y	Large	5	2	5	6	6	5	2	2	4	6	6	2
	3	18-25	Bachelor	N	N	Y	**Right**	6	2	4	6	6	4	5	5	5	2	5	4
	4	36-45	High school	N	N	N	**Right**	4	4	5	5	5	4	4	4	4	5	2	4
	5	26-35	Bachelor	N	N	Y	Small	5	2	5	6	3	5	6	2	6	6	6	6
Group A (BIM only)	6	36-45	Bachelor	N	N	N	Large	7	1	3	7	7	7	7	1	5	5	6	3
	7	18-25	Bachelor	N	N	Y	**Right**	7	5	7	7	6	7	5	2	6	6	6	6
	8	18-25	Bachelor	N	Y	N	Small	6	1	3	4	6	3	4	2	5	4	5	5
	9	36-45	College	N	N	N	Large	6	1	2	3	6	2	3	6	5	5	6	2
	10	36-45	Bachelor	N	N	N	**Right**	4	1	2	5	4	3	5	4	4	4	4	4
	11	18-25	Master	Y	Y	Y	Small	5	2	6	6	6	6	4	2	4	4	5	4
	Average						Accurac y: 36.3%	5.45	2.18	4.18	5.45	5.54	4.54	4.54	3.09	4.81	4.72	5.09	3.9

Figure 8 - Example of spreadsheet used to record data

Research Results

Quantitative analysis

Table 3 - Subjects' information

Subjects' Information in Group A(BIM only), Group B(BIM+Cardboard), and Group C(BIM+HTC VIVE)

Variable		Group A	Group B	Group C	All
		N = 11	N = 11	N = 11	N = 33
Age	18-25	5	8	8	21
	26-35	2	2	3	7
	36-45	4	1	0	5
Architecture background	Yes	1	0	0	1
	No	10	11	11	32
3D/Game background	Yes	4	7	5	16
	No	7	4	6	17
VR experience	Yes	5	5	4	14
	No	6	6	7	19

Thirty-three participants aged 18-45 joined this experiment; the majority of participants live in Zhangzhou, China. The recruitment of subjects was limited by the following criteria: (1) age 18 years or older, (2) minimum educational level equal or superior to completed high school, (3) without physical limitations, especially in the neck or back. Each subject was placed randomly in one of three test groups, a control group who observed the models only using BIM on a computer screen (Group A), a group using BIM and 360° photo using Google Cardboard (Group B) and a group using BIM and VR using a VIVE headset (Group C). Table 1 lists information about all participants in the three groups. Most of the subjects were in the 18-25 age group (n = 21, 63.6%). They represent different disciplines; only one subject acknowledged that he has an architecture background, but 42.4% participants had experience with 3D gaming/modeling or VR.

Table 4 - Comparison of mean scores on questions

Comparison of mean scores on questions: subjects with VR experience and subjects without VR experience.

Variable	Group VR		Group No-VR	
	N = 22		N = 11	
	Mean	s.d	Mean	s.d
Accuracy of room width estimation	31.82%		45.45%	
Environmental perception				
Recognition	4.91	1.10	4.70	1.05
Material	4.65	1.40	5.00	0.60
Location	5.26	0.99	5.20	1.33
Distance	4.78	1.38	4.20	1.02

Table 2 groups the participants according to their experience with 3D gaming and VR. Group VR had experience with 3D games or VR, while Group No-VR did not have any previous 3D game or VR experience. This table shows the mean scores on questions concerning environmental perception for these two groups. The actual width of the lecture hall was 22.5 meters; all participants estimated its width by picking the closest answer from the following choices: A) 10-15 meter, B) 16-20 meter, C) 21-26 meter, D) 26-30 meter. Subjects who chose C) 21-26 meter accurately estimated the width. Group VR had lower accuracy than Group No-VR (31.82% vs 45.45%) in this question, which was unexpected, and illustrates that previous VR/3D game experience did not significantly improve the subjects' accuracy in estimating room size in a virtual environment. The average score of users' responses to other questions about environmental perception were based on Likert-scale questions ranging from (1) strongly disagree to (7) strongly agree. The difference between the two groups was not statistically significant, since all mean numbers are between 4.5 to 5.5 (neutral to somewhat agree), and no significant rule in standard deviation was found in two groups. These data indicate that subjects' previous experiences with gaming or VR may affect their perception of the scale in a virtual model, but it does not indicate that this experience makes them significantly more or less perceptive of environmental effects in the model, because the observed difference was small. Since the sample size was limited, it is difficult to explain how previous VR/3D game experience contributes to people's perception of space. Future study would require more subjects to provide clues to figure out how previous VR/3D game experience would have an impact on people's feedback in a virtual environment.

Table 5 - Comparison of mean scores on all questions related to environmental perception

Comparison of mean scores on all questions related to environmental perception for Group A(BIM only), Group B(BIM+Cardboard), and Group C(BIM+ HTC VIVE)

Variable	Group A		Group B		Group C	
	N = 11		N = 11		N = 11	
	Mean	s.d	Mean	s.d	Mean	s.d
Accuracy of room width estimation	44.40%		33.30%		55.60%	
Vision clarity						
Model A(stair height = 0)	2.45	1.16	2.82	0.83	2.64	1.30
Model B(stair height = 150mm)	4.18	1.53	3.82	1.03	6.09	0.79
Model C(stair height = 250mm)	5.45	1.16	4.91	1.00	6.00	0.74
Model D(stair height = 300mm)	5.55	1.08	5.64	1.15	5.91	0.64
Stair reasonability						
Model B(stair height = 150mm)	4.55	1.56	3.64	0.98	5.64	1.07
Model C(stair height = 250mm)	4.64	1.30	4.09	0.90	3.27	0.75
Model D(stair height = 300mm)	3.09	1.50	3.36	1.37	2.00	1.13
Environmental perception						
Recognition	4.82	0.72	4.45	1.16	5.27	1.21
Material	4.73	1.14	4.73	1.21	4.82	1.34
Location	5.09	1.16	4.82	0.94	5.82	1.03
Distance	3.91	1.31	4.36	0.88	5.55	1.16

Table 3 compares subjects' reaction to specific features of the BIM models. The questionnaire asked subjects several questions about how different setups work for them to recognize some space characteristics. For example, a statement for subjects in group A is "BIM is very helpful for me to realize my location in the lecturer room." If the subject considered that it was very easy for them to realize where he/she was, the answer would be 7 (strongly agree), otherwise the answer would be 1 (strongly disagree). In general, the higher score means the more subjects agree that they better understood the spatial arrangement in this environment. The results suggest that subjects considered they had better environmental perceptions and evaluations in immersive VR setups. In the row of environmental perception (Recognition, Material, Location, Distance), group C obtained notably higher marks than group A and B, which suggests that participants thought BIM+360° photo setup was a most helpful tool to estimate the width of the room, study the material of a room, realize location and evaluate the distance between seat rows. If the user is able to better estimate distances – when the virtual estimate is closer to the estimate in the physical environment – it means that he/she better understands the spatial arrangement presented in that virtual mode (Paes D. etl., 2017). Subjects in group C also more accurately estimated the width of the lecture room than participants in groups A or B; the proportion of people who estimated the width correctly in group A, B, C was 44.4% , 33.3% and 55.6% respectively. This illustrates that HTC VIVE may allow users to perceive spatial width of a virtual space more accurately than other visualization tools. Thus, the advice or comments clients presented in the HTC VIVE environment is likely to be more solid for architects when they have the ability to accurately perceive scale.

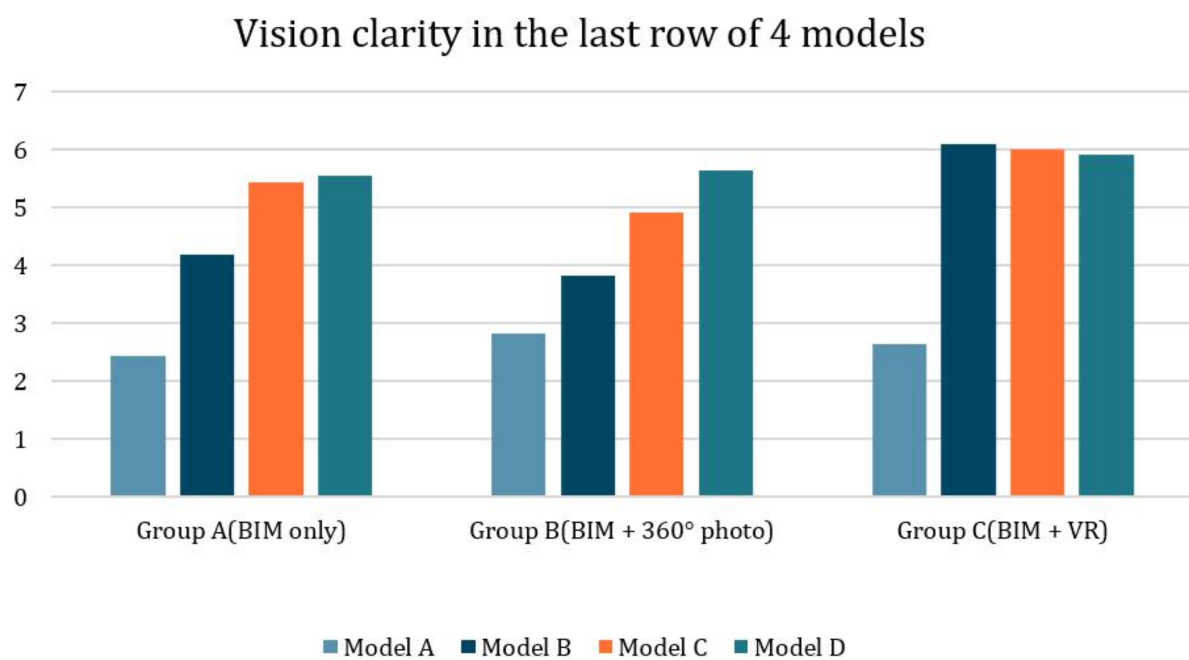


Figure 9 - Vision clarity in the last row of 4 models

In the experiment, we asked participants to stay a while in the last row to carefully assess the view toward the stage in each of the four models. They responded to statements about the view with seven-level Likert-scale statements (1 is strongly disagree while 7 is strongly agree): "In Model A/B/C/D, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance." A low mean score of all participants' responses to the statement in a specific group means fewer participants agreed that the last row of this model had a clear view. Both Table 3 and Graph1 clearly showed that Model A had the lowest score and offered the poorest view, regardless of the visualization platform used, which made sense since the floor in Model A doesn't have any slope. Similarly, most people recognized that Models C and D offered a good view of the stage, so they graded them with a high score between 5 and 6, which corresponded to 'agree' on the Likert Scale.

It is worth noting that only group C gave Model B a high score for visual clarity. This may be because only participants in this group had the power to control their viewpoint freely. An experiment conducted by Nikolic, D., and Windess, B. indicated that their subjects tended to rely on the controller to move the view instead of moving the head. Nevertheless, almost every participant in this study preferred to move their head to control the view as the photo shows. At the beginning, all subjects were facing the computer screen before wearing the VR headset. Subjects were able to freely look around by moving the head and body instead of using controllers to roam in the virtual world. So even if subjects turned their back on the computer, they still kept a normal view in the VR world as shown on the screen. Both Cardboard and HTC VIVE have more natural and flexible interaction mode and unconstrained head tracking. This kind of convenient interaction makes participants have more time and chance to perceive the spatial objects, patterns and other information in the virtual scene. However, the viewpoint height in Cardboard was fixed while subjects were able to adjust their sitting position or improve their view by changing their head position to get a better view in HTC VIVE, just as they would in reality. Most people already know that a suitable step height should be around 150mm for safety from their lived experience, even if they do not have any architectural knowledge. Hence, it is reasonable to conclude that when the virtual behavior is closer to the behavior in the physical environment, the simulation results are closer to reality. The more realistic simulation environment enables to create engaging experiences and stimulate users' natural behavior. The study was able to establish that immersive VR provides a clearer representation of a physical environment than BIM alone or BIM with 360° photo, and it offers subjects the ability to understand the space more closely to reality.

Figure 10 - Experimental photos

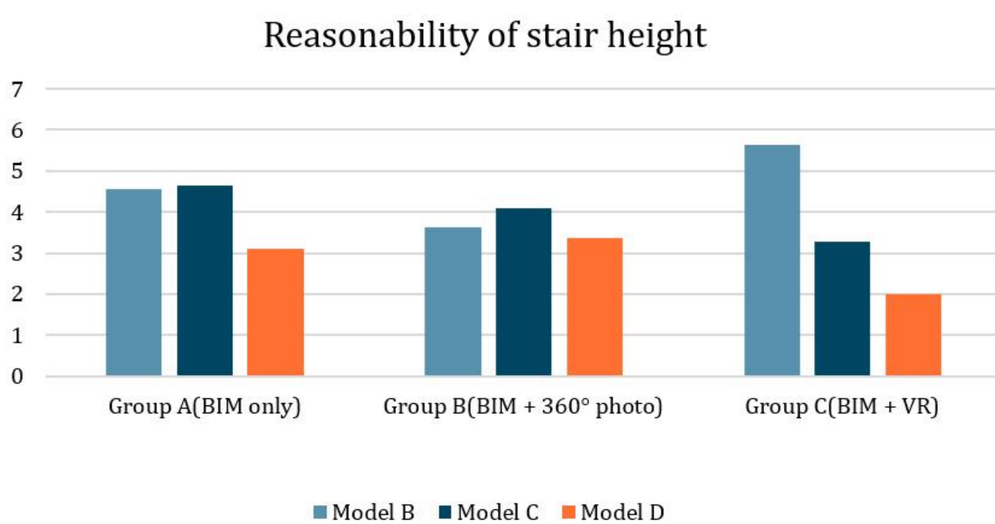


Figure 11 - Reasonability of stair height

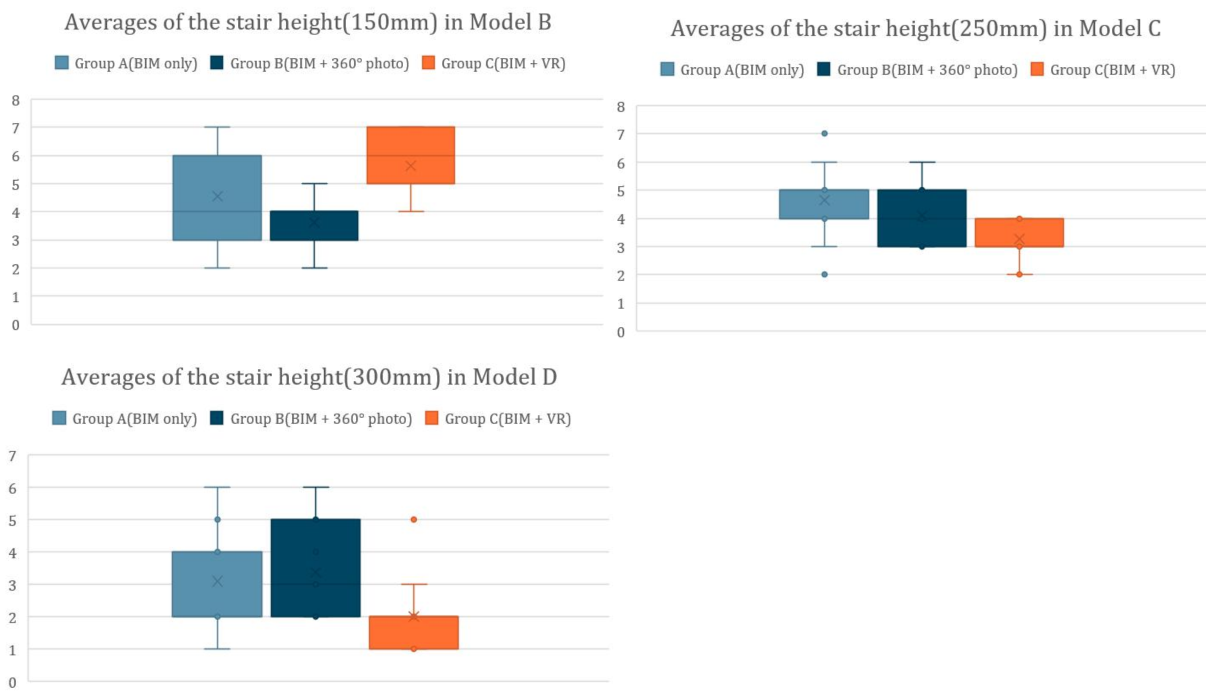


Figure 12 - Average of the stair height in 3 models

Graph 2 uses the data on "stair reasonability" in Table 3 to compare participants' evaluation of the stair heights in the model. The data dispersion of the scores recorded by group B and group C are, in almost every instance, less than the s.d. of group A's responses to stair reasonability. The variance of opinions toward the three models with a sloped floor in group C is significantly larger than in groups A or B. This suggests that group C judged Model B most favorably and Model D least favorably, while Groups A and B judged these three models almost equally, with a slightly less favorable view of Model D. Graph 3 shows that group C's evaluations of all three models had the smallest deviation, which means that a majority of the participants in group C evaluated a particular model similarly, with more consistency and more confidence. In other words, many subjects in group C were able to figure out Model B was the reasonable one, while subjects in groups A and B did not reach the same conclusion. On the contrary, a relatively large amount of variation in the group A's responses may reflect participants' uncertainty about their spatial and visual perception, because they were only viewing models through a 2D screen. Participants in group B and C may have felt more confident about their perceptions in the 3D virtual environment since their spatial experience is likely to be more reliable and more like the real world, while group A did not judge the models as consistently. An extreme example of this can be seen in the graph for model D, in which group A participants, who experienced the model in BIM only scored it as low as 1 (strongly disagree he/she had a clear view in the last row) and as high as 6 (agree he/she had a clear view in the last row). This wide variation implies that viewing models on screen may not convey architectural ideas effectively. On the other hand, the spread was much smaller for participants who evaluated model D using VR. We may conclude from Graph 3 that users of VR judge space experience more consistently, which indicates better perception of the interior and more confidence in their evaluations. These findings supported the previous conclusions of Hannah et al., 2012 and Lukačević, F. et al., 2020, indicating that participants would be more confident in their space recognition in the VR environment.

Figure 13 - Participant with Google Cardboard(left) vs with HTC VIVE(right)

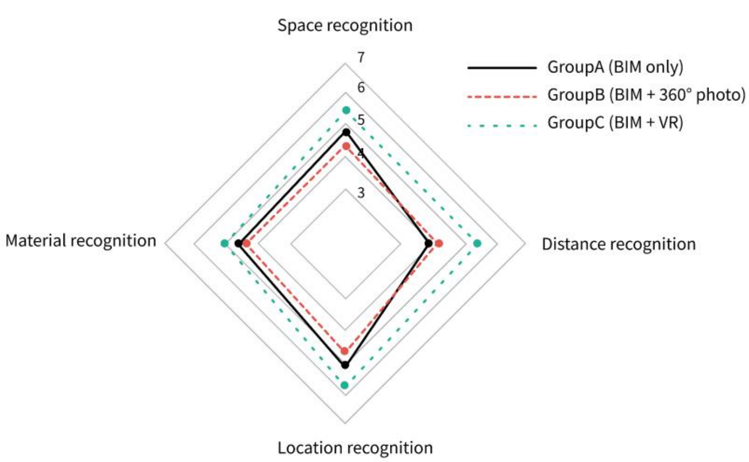


Figure 14 - Radar chart of environment perception of 3 groups

Graph 4 uses the data on "environmental perception" in table 3 to show participants' evaluation of various details (recognition of space, material, location and distance) in the lecture hall. It illustrates that the immersive VR group (group D) gave the highest ratings, which shows that they found the technology useful for understanding virtual characteristics of a space, including shape, color, material, distance and scale. Normally, these aspects of a building get worked out after repeated deliberation in the design stage. While it is almost impossible to build up every design scheme in reality, we can use the BIM+VR model to adjust each variable separately and place subjects into revised environments to observe their perception and get instant-feedback, thus eliminating blind spots and flaws to support design decision-making.

Quality analysis

Overall, the whole experiment ran smoothly, and participants cooperated actively. One thing worth noting is that group C (BIM + VR) offered the most emotional feedback. They had both good and bad opinions about HTC VIVE, and while they did not necessarily favor VR as a way of looking at BIM models, they had more to say about the process and they expressed their ideas more positively than participants in the other groups. One subject in group A pointed out that it was unreasonable to view 4 models one by one since he almost forgot the first model by the time he was looking at the fourth one. In a real design review meeting, architects almost always present multiple schemes together to improve work efficiency and allow direct comparison; this experiment did not offer the opportunity to examine more than one model at once. Just one participant in group A provided this type of feedback. Participants in group A, had less to say, which may be because they were placed in a more passive state, since they just viewed the still model and associated data. However, participants in the other groups spoke actively in the discussion. One participant in Group C commented that she felt a little fear looking down from the last row of Model D in immersive VR, and this made her realize that the stair height in Model D was abnormal. Another subject stated that he was surprised to find that the space looks larger in VR than in 2D BIM and that the differences between stair heights in the models are more vivid in -VR. One said that the step of Model D was too high and made him feel like he could touch the ceiling when he stood in the last row (in the virtual world). Another participant suggested that I should raise the height of the blackboard so he could have a better view from the seats in the back row. These details were unanticipated, suggesting that small problems that may be difficult to perceive in a digital model are much more evident when it is experienced in VR.

Some problems from participants' feedback were noteworthy. A few subjects complained about Google Cardboard and HTC VIVE. Several people had trouble keeping the phone from sliding around in the Cardboard headset, so they had to hold onto the Cardboard when turning around. All participants in group C used the same HTC VIVE headset, so we had to adjust the tracker belt repeatedly to fit the user's head before the official experiment. This was a tedious process. Someone also reflected that he might have begun to feel uncomfortable and dizzy if he had been in the simulation for a long time, since the headset put a lot of weight on his nose.

Another potential problem was safety. We asked subjects in group C to view the whole room from the three required seats in the last row, but that they could also walk around freely. The viewpoint in the virtual world aligns with the subjects' eyes, so the connection between virtual position and body position required subjects to repeatedly stand up or sit down to simulate the proper view in the lecture hall space. But subjects could see nothing in the physical test room once they put on the headset, so they definitely needed help to find the right place to sit down. Most subjects said that it was comfortable and interesting to interact with the simulation but that the repeated action was tiring. In addition, the lower loading speed of rendering VR images also consumed their patience. There was a lag time in the VR, and subjects had to wait a while for the image to come up in the headset.

Data Analysis

Data gathered in this study show that compared to the BIM with 360° photo and BIM only setups, VR promotes sensitivity to the digital model and provides better spatial perception of it. The study process showed that the most convenient and least time-consuming setup was BIM only, but it was also least effective in conveying information to subjects. 360° photo was a convenient means of achieving low-cost immersive stereoscopic viewing experiences. Although its visual effect was general, it did inspire subjects to be more interested in exploring the space. VR required much more time for subjects to complete the experiment than 360° photo, since it included a lot of effort to adjust the headset, wait for the software to load, render and allow subjects to be familiar with how to operate VR, but these preparations strengthened the interaction between users and the virtual space; it thus appears to foster trust and clearer communication. From the subjects' feedback, VR enabled them to have dynamic and continuous experience with the architecture and it best simulates how they might behave in it if it were a physical space. This interesting and vivid tour using VR inspired them to take a more active approach to be involved in the study. 360° photo also enriched the users' feeling for the digital model, but this feeling seemed to be less vivid, since the subjects could only view space from specific positions and could not move freely in the model. Subjects commented that it was boring and tedious to just look at the model through a 2D screen, since it was hard for them to understand the principle of BIM technology or visualize building data in a short time; subjects who used the VR platforms were more enthusiastic about the experience.

Study data showed that participants in all groups could correctly understand the ineffectiveness of the stepless, zero-slope design in Model A for the audience's sightlines. However, only Group C, which used immersive VR, noted that the step height of Model B is reasonable while the step height of Model D is quite unreasonable. This appears to be because immersive VR provides the most realistic view of the space and elicits the most detailed response from users. In reality, an ordinary person using physical steps can quickly realize that 150 mm high steps are normal while 300 mm high steps are unreasonable and dangerous. In addition, data from group A (BIM only) had the largest variance, illustrating that subjects of this group had significantly different attitudes toward the same model. For example, some subjects considered the 300 mm stair height to be unreasonable, while others did not note that this was a problem in the design. This suggests that for people without experience looking at digital architecture models, BIM did not help them to perceive the information well. VR clearly improved subjects' ability to perceive this information; most subjects in Group C had similar opinions about the clarity of sightlines and the appropriateness of step heights. To put this in a different context, when architects hold a review meeting, they certainly do not want to get huge differences in comments and opinions from the audience, which would be a great obstacle for them to move on and carry out the next steps in the design. On the contrary, relatively consistent opinions can help architects to unify ideas and further promote the design. W. Xiao et al., have come up with a closed-loop design framework of “design-simulation-perception-feedback-design”, and consensus in clients’ feedback is very important for architects to quickly summarize, analyze then move to the next design round.

When asked to estimate the width of the space in the model participants who had VR experience or 3D gaming experience did not appear to judge more accurately than those who did not have these experiences, regardless of what visualization platform they used. However, participants who used immersive VR in the experiment were able to judge the width of the space more accurately than subjects in the other groups. Although the sample size was small in this experiment, this could help to demonstrate that immersive VR benefits people’s overall spatial perception, whether they have experience with the technology or not. Finally, the fact that Group C gave the highest ratings for environment perception shows that immersive VR helps people to better understand many different characteristics of the space-defining elements.

Conclusion and Reflection

In summary, this experiment indicated that BIM+VR has the benefit of helping subjects to perceive space closer to reality, and subjects in the VR setup had a more consistent spatial experience. Data obtained in this study showed that VR enables users to be more sensitive toward scale design in space and encourages them to offer opinions more actively. Architects have been working hard to improve design by gathering substantial feedback and enabling clients to get anticipatory effect. The results suggest that both VR and 360° photo can help clients and non-experts participate more fully in the design process in this small simulated design review, showing the possibility of improving formal architectural design decision making.

There are some limitations and deficiencies in this study. One of them is the size sample. Recruiting a great number of subjects became difficult during the COVID-19 lockdown. The sample size of 33 is small. Besides, all subjects are Chinese and many of them are young people, who are familiar with VR technology. Nonetheless, if the subject group is made of more diverse people with large age cover, the experiment results may differ as well. For future experiments, a larger sample size should be implemented to provide more definitive results.

This study did not examine whether the order of presentation (the order that each subject experienced the model is A, B, C, D, in which steps rise gradually from 0 to 300mm) had any effect on the result. In addition, since some subjects might prefer to avoid extreme choices (model A and model D) mixing the order of the models may have affected the results. Eliminating potential influencing factors could help to produce more definitive results about which setup helps subjects perceive spatial features more accurately. In addition, the novelty or attention that the new technology brings could fade over time. Subjects may feel highly interested and excited when he/she first uses VR to view the first model then scores this model higher, but he may already feel bored and just want to finish it quickly for the last model. This change of mind may also affect the final result.

Subjects in group B and C experienced the process of repeatedly taking off and putting on the headset to view the computer screen and VR scene, which was distractive and impacted the fluency of the experience, and also may lead to the forgetfulness of the first model as they viewed the other models. One possible reason would be that subjects are placed in a room which has nothing to do with the design to experience. If subjects have the chance to experience VR in the place where the new building is going to be built, they will feel more immersive. The interaction and comparison with the real site can enhance the user's sense of expectation so as to reduce the fatigue caused by repeatedly taking off the headset.

Another problem concerns the quantity of equipment available for the experiment, which included only one Google Cardboard and one HTC VIVE headset. Subjects therefore had to be tested one by one, which limited the kinds of discussions that might occur in a real design review meeting. If architects plan to utilize VR to review designs with clients or user groups, they should prepare a sufficient quantity of VR headsets in order to bring the group into real-time discussion for optimum results. This raises other important issues: (1) cost: several VR headsets, which are themselves expensive, require expensive computers with high-capacity hardware configurations. (2) time: many devices need a long debugging time on site, then affect the whole meeting efficiency. (3) safety: Although none of the subjects in this experiment reported dizziness or eye-strain, this may be because the subjects were mainly young people. Some of them did complain that the headset was heavy and uncomfortable. The experimental setup did not allow recording how every subject was moving and interacting with the VR equipment; however, anecdotally, it appeared that some body actions, like craning necks or adjusting position, might indicate whether people had trouble with the VR system. Despite clear empirical data from this experiment, there are potential risks, and these must be evaluated before VR can be implemented broadly as an effective design support tool for non-experts. In 2019, Microsoft introduced the Hololens 2 headset, marked a turning point for lightweight design in the VR field. This and other thin, light and high performance headsets may solve some problems with discomfort for users, but they will not eliminate all ergonomic and safety issues. Finally, in this experiment subjects could walk around and sit down to simulate their viewpoints in virtual reality, since HTC VIVE can track head motion and body movement well. Problems arose because subjects were effectively blind to their physical environment. Participants had no way to see the physical world once they put on a headset, and some of them felt nervous and insecure when moving around. This experiment was conducted in a limited space with only 3 m x 3 m available, so subjects could not move beyond the testing room, which was much smaller than the space depicted in the digital model. They were afraid to walk around freely, and all body movements were a little stiff. In most cases, subjects walked around the model by pressing a control stick to virtually move while standing still. In other words, a capacious and accessible room is necessary for many people to utilize VR fully.

Because people's observation in the VR world is a 360 ° panoramic experience, small details that are hard to be noticed in traditional 3D models would be easily noticed in the VR scene, which is exactly what architects expect. Therefore, VR can bring its strength into full play only when every detail of the project model is brought to sufficient resolution. The models used in this study were 4 lecture halls, which were relatively simple indoor spaces with simple furniture and other details such as seats, platform and figures used to simulate the hindrance of the sight lines. In general, the overall models were highly completed since the simple furniture arrangements in four lecture halls were sufficiently detailed for participants to perceive subtle aspects of the room. However, if a large comprehensive building, such as a shopping mall or a gymnasium were used, the application of VR technology puts high demands on the completion and authenticity of the model. In this case, the advantages of BIM's information aggregation would be enlarged further. With the rapid development of digital information, building functions, modeling and data are becoming more complex. Compared with the traditional CAD graphic design or hand drawing, BIM's ability to systematically integrate information is particularly prominent. Nonetheless, it is difficult for architects or clients to fully visualize the virtual model space using only BIM on a computer screen. Thus, the combined advantages of information integration in BIM and immersive experience of VR has great potential for improving architectural visualization.

In the aspect of experimental design, this study could be better by improving the following aspects. (1) Models used in this experiment are a series of lecture halls with simple space arrangement and function. If a larger and fully functional building would be used in the future study, it can induce more complex user behavior to compare their virtual travel. For example, a complex shopping mall model would be used to observe subjects' navigation routes. (2) For evaluating group design reviews, future research could include more VR setups, or introduce a projector for participants without a headset by expanding the image of one headset for everyone to see. Since both designers and clients could view the VR projection together, the designer could use an assistant tool to point out the specific features to clients who are in the virtual world, thus allowing the discussion to become more natural and efficient. (3) This experiment only used questionnaires and user interviews to obtain subject's feedback. In the future study, more quantitative research methods should be designed to more accurately explore subjects' space cognition and gaze search, such as path tracking and gaze trajectory. The visual analysis could be extended from 2D plan to 3D space in immersive virtual reality. By combining digital models with eye/path tracking devices, it would be easier for architects to analyze clients' spatial observations (W Xiao et al., 2019).

Future Research

This study noted that being presented in VR for a long time would cause fatigue and may change the study conclusion. Therefore, future research should explore the effects of the duration of VR and potential mental workload to help architects figure out the best time to utilize VR. In addition, augmented reality (AR) technology is also another effective way to offer audiences new kinds of sensory experience by promoting their learning engagement in the design review. The future research could make efforts to provide guidance for architects to make decisions on their VR or AR adoption.

Conclusions

Overall, this study supports the proposal that VR technology can improve the ability of non-experts to evaluate BIM models. The results offer several noteworthy findings: First, VR provides subjects with a sense of immersive experience that 3D BIM on a 2D-screen cannot achieve. Second, it is easier and quicker for subjects to process information and spatial relationships in the VR environment. Third, a more immersive device (HTC VIVE) promotes stronger sensitivity to human scale and provides overall better spatial perception. Last, VR enables subjects to be more confident in their assessment of scale and other spatial cues and inspires people to actively offer their opinions in design review.

This study bridges the gap between research on spatial perception in the use of BIM+VR normally done with students and nonprofessional people(clients) and tries to recognize the general process of integrating BIM and VR. The findings suggest that "BIM+VR" provides a basis for design decision-making in the preliminary design process by supporting users' perceptions of the space. Clients are prone to have incomplete understanding of a BIM model, which may lead to confusion or to impractical comments. The experiment conducted in this thesis shows that clients using a fully immersive virtual reality perform better in the way they review and evaluate the space depicted in a BIM model. The results suggest that, compared with the conventional design review meeting (led by architects and supplemented with 2D drawings or 3D models), a hybrid review environment, which integrates the high functionality of BIM and the immersion of VR, would work well as a decision support environment and can have a positive impact on design communication. This new BIM+VR platform can connect architects and other stakeholders together for interactive design and real-time feedback, allowing issues to be uncovered and addressed earlier in the design process than with BIM alone.

On the other hand, the experiment showed that both VR and 360° photos still have some limitations and inconveniences. Nevertheless, new tools are in development, and old ones can be adapted to suit designers' needs. The goal is to solve the problems of information management and design communication. Therefore, if VR wants to have large scale application in industry, it should deal with some problems: (1)meet the spatial position tracking of head and hands at the same time, which is the defect of Google Cardboard, (2) have fast location ability and high positioning accuracy, (3) be small size, lightweight and have strong portability (4) have affordable price. VR technology is developing at a rapid pace and newer hardware may change the way architects utilize it in industry as well.

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Appendix A: Pre-Questionnaire

- What is your age?
    a. 18-25
    b. 26-35
    c. 36-45
- What is your highest academic level?
    a. High school or equivalent
    b. Some college coursework completed
    c. Bachelor's degree
    d. Master's degree
    e. Doctorate degree
- Do you have any architectural background or experiences? (such as being in an architectural program)
    a. Yes
    b. No
- Did you play video games or use 3D models before?
    a. Yes
    b. No
- Did you experience virtual reality before?
    a. Yes
    b. No

Appendix B: QuestionnaireA

For GroupA

- Do you find the difference between four lecture halls?
    - Width
    - Height
    - Slope
    - Decoration
    - No difference
- Please estimate the room width of last lecture hall
    - 10-15 meter
    - 15-20 meter
    - 20-25 meter
    - 25-30 meter
- In Model A, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

In Model B, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

In Model C, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

In Model D, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

- I think the single stair height in model B is reasonable

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree

I think the single stair height in model C is reasonable

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree

I think the single stair height in model D is reasonable

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree

- BIM is very helpful for me to estimate the depth/width/height of the

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree

room

BIM is very helpful for me to study the material/color of a room.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree

BIM is very helpful for me to realize my location in a room

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree

BIM is very helpful for me to evaluate the distance between seat

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree

rows

BIM is very helpful for me to evaluate whether the design of stair height in this lecture hall is reasonable

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree

- What BIM model features contributed to your understanding of the lecture hall design? Please explain your reason(s)

- What do you dislike in the BIM environment? Please explain your reason(s).

Appendix C: QuestionnaireB

For Group B (BIM+Google Cardboard) and Group C (BIM+HTC VIVE)

- Do you find the difference between three lecture halls?
    - Width
    - Height
    - Slope
    - Decoration
    - No difference
- Please estimate the room width of last lecture hall
    - 10-15 meter
    - 15-20 meter
    - 20-25 meter
    - 25-30 meter
- In Model A, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

In Model B, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

In Model C, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

In Model D, I can clearly see the speaker on the stage from three highlighted seats' viewpoints without eyesight disturbance.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

- I think the single stair height in model B is reasonable

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

I think the single stair height in model C is reasonable

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

I think the single stair height in model D is reasonable

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

- BIM + Cardboard/HTC VIVE is very helpful for me to estimate the depth/width/height of the room

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

BIM+ Cardboard/HTC VIVE is very helpful for me to study the material/color of a room.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

BIM + Cardboard/HTC VIVE is very helpful for me to realize my location in a room

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

BIM + Cardboard/HTC VIVE is very helpful for me to evaluate the distance between seat rows

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

BIM + Cardboard/HTC VIVE is very helpful for me to evaluate whether the design of stair height in this lecture hall is reasonable

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

- Overall, which tool would you prefer to use in future to understand architectural models?
  - BIM only
  - VR only

    - BIM + VR
    - Same
- What VR features contributed to your understanding of the lecture hall design? Please explain your reason(s)

- What BIM model features contributed to your understanding of the lecture hall design? Please explain your reason(s)

- What do you dislike in VR? Please explain your reason(s)

- What do you dislike in BIM? Please explain your reason(s)